ASSESMENT OF CACTUS POTENTIAL AS A NATURAL COAGULANT IN WATER TREATMENT

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ABSTRACT

Assessment of Opuntia ficus-indica Cactus Potential as a Natural Coagulant in water Treatment

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The treatments of water with chemical coagulants have a number of disadvantages such as concern for human health, cost of chemicals (especially in developing countries), and sludge management among others. It is in this light that this research was carried out to check the effectiveness of powder extracted from Cactus (*Opuntia Ficus Indica*) in removing turbidity from surface water sources. OFI Powder was prepared by drying the pad in an oven and grounding the dried pad by a coffee grinder. The results obtained were compared with chemical coagulants (PolyDADMAC and Alum) and with also the other natural coagulant Moringa Olifera. Two surface water sources were used in Jar test experiment (Legedadi and Geffersa reservoir waters). OFI powder turbidity removal efficiency reached 99.4 % and 95.7 % for raw waters from Legedadi and Geffersa reservoirs respectively. Coagulation using OFI powder did not influence the PH of the water. Total dissolved solids and conductivity increased gradually with increasing concentrations OFI. Turbidity removal efficiency of OFI was comparable to that of chemical coagulants for both water samples. When compared with Moringa olifera, OFI showed better turbidity removal efficiency. The use of OFI powder with Alum did not show good turbidity removal efficiency. In contrast the use of OFI powder with Moringa Olifera showed good turbidity removal efficiency and reduced usage OFI powder. Factors affecting the effectiveness of OFI powder were examined initial turbidity level did not affect the turbidity removal efficiency but decrease in temperature affected OFI powder efficiency. At different PH values OFI showed different turbidity removal efficiency the Optimum result was found at PH 10 and the worst at PH 4. Findings from this study indicate that OFI, a natural coagulant, can be a potentially viable substitute to chemical coagulants in treatment of water.

Keywords: OFI powder: Moringa Oleifera; coagulation;

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LIST OF ABBREVIATIONS

AAWSA	Addis Ababa Water and Sewerage Authority
EPI-DMA	Epichlorhydrin-dimethylamine
EC	Electric Conductivity
HBPWS	Handbook of Public Water Systems
MDG	Millennium Development Goal
MO	Moringa Olifera
NOM	Natural Organic Matter
NTU	Nephelometric Turbidity Unit
OFI	Opuntia Ficus Indica
PolyDADMAC	poly diallyldimethyl ammonium chloride
STDEV	Standard Deviation
TDS	Total Dissolved Solid
UNDP	United Nations Development Programme
WHO	World Health Organization

1. INTRODUCTION

1.1 BACKGROUND

Access to clean and safe drinking water is a human right; however, the availability of potable water is a major concern in both developed and developing countries. Water treatment offers the benefit of potable water in terms of quality (reduced level of contaminants) and quantity (availability). The world is facing formidable challenges in meeting the rising demands for safe drinking water supply due to population growth, increasing pollution of water bodies from several industrial and agricultural activities, drought and competing demands from a variety of users.

Due to limited alternatives, surface water either from rivers or rain fed ponds has become one of the main sources of water supply. This water is vulnerable to various forms of pollution generated from different sources. The use of surface water stands at a surprisingly high 3 per cent of the global population, or 187 million people. Most of these people 94 per cent are rural inhabitants, and they are concentrated in sub-Saharan Africa. In fact, 19 per cent of rural dwellers in sub-Saharan Africa and 39 per cent of rural residents in Oceania rely on surface water for drinking and cooking (JMP report by WHO and UNICEF 2012).

The Millennium Development Goal 7, Target 7C which calls on countries to “Half by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation” is met. The drinking water target has thus become one of the first MDG target to be met. While this tremendous achievement should be applauded, a great deal of work remains.

First, huge disparities exist. While coverage of improved water supply sources is 90 per cent or more in Latin America and the Caribbean, Northern Africa and large parts of Asia, it is only 61 per cent in sub-Saharan Africa. Coverage in the developing world overall stands at 86 per cent, but it is only 63 per cent in countries designated as ‘least developed’. Similar disparities are found within countries between the rich and poor and between those living in rural and urban areas (JMP report by WHO and UNICEF 2012).

Second, complete information about drinking water safety is not available for global monitoring. Systematically testing the microbial and chemical quality of water at the national level in all countries is prohibitively expensive and logistically complicated; therefore, a proxy indicator for water quality was agreed upon for MDG monitoring. This proxy measures the proportion of the population using ‘improved’ drinking water sources, defined as those that, by the nature of their construction, are protected from outside contamination, particularly faecal matter. However, some of these sources may not be adequately maintained and therefore may not actually provide ‘safe’ drinking water. As a result, it is likely that the number of people using safe water supplies has been over-estimated (JMP report by WHO and UNICEF 2012).

Finally, more than 780 million people remain unserved. Although the MDG drinking water target has been met, it only calls for halving the proportion of people without safe drinking water. More than one tenth of the global population still relied on unimproved drinking water sources in 2010 (JMP report by WHO and UNICEF 2012).

Water-related diseases cost 443 million school days each year, equivalent to an entire school year for all seven-year-old children in Ethiopia (UNDP, 2006). Almost half of these days are lost due to intestinal parasites transmitted through water and faecal material. More than 150 million children of school going age are severely affected by the intestinal helminths such as roundworm, whipworm and hookworm. Children with infections are twice as likely to be absent from school as those without and they perform poorly even when in school (UNDP, 2006).

Beyond the human waste and suffering, the global deficit in water and sanitation is undermining prosperity and retarding economic growth. Productivity losses linked to this deficit is retarding the efforts of millions of the world’s poorest people to work their way out of poverty and holding back development of these countries. Less attention has been paid to the economic costs of the crises in water and sanitation and to the implications of these costs for poverty and prosperity (UNDP, 2006).

Various methods are used to make water safe and attractive to the consumer. The method employed depends on the character and source of the raw water e.g. surface water, groundwater. For surface water, coagulation-flocculation followed by sedimentation, filtration and disinfection, often by chlorine, is used worldwide in the water treatment industry before distribution of the treated water to consumers.

Coagulation of waters to aid their clarification has been practiced since ancient times. Coagulation and flocculation are used in both water and wastewater treatment process. In water treatment when particles are slow to settle or are non-settling, the process is speeded up by coagulation and flocculation through the addition of certain chemicals known as coagulants. Coagulation-Flocculation can also be applied to enhance the removal of solids in highly concentrated natural waters that contain significant amount of settleable solids (Guibai and Gregory, 1991). This process plays a major role in surface water treatment by reducing turbidity, bacteria, algae, color, organic compounds and clay particles. These processes are effective at removing fine suspended particles that attract and hold bacteria and viruses to their surface. They can remove up to 99.9% of the bacteria and 99% of the viruses from water supplies (CRC, 2003). Coagulation and flocculation are critical operations in water treatment. Ineffective coagulation affects sedimentation, filtration, and disinfection, and results in poor quality treated water, increased chemical usage and ultimately higher production costs.

In developing countries treatment plants are expensive, the ability to pay for service is minimal and skills as well as technology are scarce. In order to alleviate the prevailing difficulties, approaches should focus on sustainable water treatment systems that are low cost, robust and require minimal maintenance and operator skills. Locally available materials can be exploited towards achieving sustainable safe potable water supply.

The use of natural materials for treatment of drinking water in some parts of the world has been recorded throughout human history. However, the natural materials have not been recognized or duly supported due to lack of knowledge on their exact nature and the mechanism by which they function. As a consequence, the natural materials have been unable to compete effectively with the commonly used water chemicals (Ndabigengesere & Narasiah, 1998). In recent years there has been a resurgence of interest in using naturally occurring alternatives to currently used coagulants for water treatment in developing countries (Jahn, 1981, 1988), mainly due to cost implications that are associated with inorganic chemicals, synthetic organic polymers and disinfectants (Schultz & Okun, 1984). There is also an interest in reusing some of the by-products from natural coagulants in other enterprises (Kawamura, 1991).

1.2 STATEMENT OF THE PROBLEM

In general coagulants in water and wastewater treatment can be divided in three parts: inorganic (e.g. Aluminum sulfate, Ferric chloride, Polyaluminum chloride), synthetic organic polymers (e.g. Polyacrylamide derivatives and Polyethylene imine) and natural coagulant (e.g. chitosan and plant extracts). There are constraints encountered in the use of chemical coagulants, such as scarcity of foreign currency for importation, the costs of these chemicals has been increasing at an alarming rate in developing countries, most of the water treatment companies cannot cope with the high costs due to declining revenues and funding, Under-dosing of chemicals so as to meet the increasing water demand leading to production of poor quality drinking water and inadequate supply of chemicals. Although Aluminum sulfate (alum) is the most commonly used coagulant in the developing countries, studies have linked it to the development of neurological diseases (e.g. pre-senile dementia or Alzheimer’s disease) due to the presence of aluminum ions in the drinking water (Jekel, 1991). More so, large non-biodegradable sludge volumes are produced containing residual aluminum sulphate needing treatment facilities to prevent further contamination into the environment.

In addition, alum has raised a number of concerns including 1) its reaction with natural alkalinity present in the water; leading to pH reduction (lime is added for pH adjustment which is considered as an additional cost for water treatment companies) 2) demonstrates low coagulation efficiency in cold waters. Furthermore, optimal implementation of alum requires technical skill and training.

Iron salts and polymeric compounds also are used as coagulant, but with limited effect and outcome. In general one of the main problems of these coagulants is production of high volume sludge that doesn't lose its water easily and causes problem (Haarhoff and Cleasby,1988; Letterman and Pero, 1990). Polyelectrolytes are also questioned due to the toxicity and carcinogenetic potential of the monomers used for their synthesis, as in the case of polyacrylamide, or due to the possible interference of the residual product in water with disinfection products, as in the case of PDADMAC (Bolto *et al.*, 2007). For these reasons, there is a need to design and develop appropriate Point-of-use (POU) treatment technologies for developing communities. One component of this may be alternative coagulants that are less expensive, renewable, locally available, and readily implementable.

The combination of the concerns with chemical coagulants and the strong push to meet the drinking water needs of the developing world have led to the recent growing interest in using plant based natural coagulants in both the developed and developing world. The use of natural materials of plant origin to clarify turbid raw waters is not a new idea. Natural coagulants have been used for domestic household for centuries in traditional water treatment in rural areas. A number of effective coagulants from plant origin have been identified: Nirmali (Tripathi et al., 1976); Okra (Al-Samawi and Shokralla, 1996); red bean, sugar and red maize (Gunaratna et al., 2007), *M. oleifera* (Jahn, 1988), Cactus (*Opuntia Ficus Indica)* and a natural coagulant from animal origin; chitosan. Natural mineral coagulants have also been used including fluvial clays and earth from termite hills.

The most studied of the natural coagulants is *M. oleifera*, whose efficiency has been reported for turbidity removal as well as antimicrobial properties. Apart from several advantages of the MO protein over chemical coagulants, the main drawback in using the crude extracts of MO seeds in water treatment is the release of organic matter and nutrients to the water. Analogous reports for Cactus pear (*Opuntia Ficus Indica)* are scarce. Consequently, this research deals with purification of the coagulant and treatment of surface waters with the use of purified OFI coagulant.

1.3 OBJECTIVE OF THE STUDY

1.3.1 General objective

The general objective of the study is to evaluate the performance and determine the optimum dosage of natural coagulant derived from OFI as a coagulant in treating surface water in terms of turbidity.

1.3.2 Specific Objectives

The specific objectives of the study are:

1. To compare the performance of PolyDADMAC and OFI in terms of turbidity removal.
2. To compare the performance of Alum and OFI in terms of turbidity removal and their effect on PH.
3. To compare the performance of Moringa Olifera and OFI in terms of turbidity removal.
4. To evaluate the performance of combined coagulants of Alum and OFI in treating surface water and to suggest an optimum combination of coagulants based on turbidity removal.
5. To evaluate the performance of combined coagulants of Moringa olifera and OFI in treating surface water.
6. To evaluate the factors affecting coagulation effectiveness of OFI.
7. To give an insight for further research on OFI.

2. LITERATURE REVIEW

2.1 PARAMETERS FOR DRINKING WATER QUALITY

2.1.1 Turbidity

Turbidity is a principal physical characteristic of water and is an expression of the optical property that causes light to be scattered and absorbed by particles and molecules rather than transmitted in straight lines through a water sample. It is caused by suspended matter or impurities that interfere with the clarity of the water. These impurities may include clay, silt, finely divided inorganic and organic matter, soluble colored organic compounds, and plankton and other microscopic organisms. Typical sources of turbidity in drinking water include the following (EPA, 1999)

- Waste discharges;
- Runoff from watersheds, especially those that are disturbed or eroding;
- Algae or aquatic weeds and products of their breakdown in water reservoirs, rivers, or lakes;
- Humic acids and other organic compounds resulting from decay of plants, leaves, etc. in water sources; and
- High iron concentrations which give waters a rust-red coloration (mainly in ground water and ground water under the direct influence of surface water).
- Air bubbles and particles from the treatment process (e.g., hydroxides, lime softening)

Simply stated, turbidity is the measure of relative clarity of a liquid. Clarity is important when producing drinking water for human consumption and in many manufacturing uses. Once considered as a mostly aesthetic characteristic of drinking water, significant evidence exists that controlling turbidity is a competent safeguard against pathogens in drinking water.

Excessive turbidity, or cloudiness, in drinking water is aesthetically unappealing, and may also represent a health concern. Turbidity can provide food and shelter for pathogens. If not removed, turbidity can promote regrowth of pathogens in the distribution system, leading to waterborne disease outbreaks, which have caused significant cases of gastroenteritis throughout the world. The adsorptive properties of suspended particles can lead to a concentration of heavy metal ions and biocides in turbid waters. Turbidity has also been related to trihalomethane formation in chlorinated water. In addition, turbidity has often been associated with unacceptable tastes and odors (Turbidity Guidelines, 1995). Although turbidity is not a direct indicator of health risk, numerous studies show a strong relationship between removal of turbidity and removal of protozoa (EPA,1999).

Low filtered water turbidity can be correlated with low bacterial counts and low incidences of viral disease. Positive correlations between removals (the difference between raw and plant effluent water samples) of pathogens and turbidity have also been observed in several studies. In fact, in every study to date where pathogens and turbidity occur in the source water, pathogen removal coincides with turbidity/particle removal (Fox, 1995).

In all processes in which disinfection is practiced, the turbidity must be always below, preferably 1 NTU and always less than 5 NTU; otherwise the particulate matter will interfere with the efficiency of disinfection, partly by exerting a disinfectant demand and partly by shielding microorganisms, even in the presence of a residual disinfectant otherwise sufficient to ensure a kill. To exceed turbidity limits suggests both a significant deterioration in water quality and a significant health hazard (WHO, 1984).

2.1.2 PH

PH is a measure of the hydrogen ion concentration of the water. The pH of water indicates whether the water is acid or alkaline. The measurement of pH ranges from 1 to 14 with a pH of 7 indicating a neutral solution, neither acid nor alkaline. Numbers lower than 7 indicate acidity; numbers higher than 7 indicate alkalinity. Drinking water with a pH of between 6.5 and 8.5 is generally considered satisfactory. Acid waters tend to be corrosive to plumbing and faucets, particularly if the pH is below 6. Waters with a pH of above 8.5 may tend to have a bitter or soda like taste. The pH of water may have an effect on the treatment of water and also should be considered if the water is used for field application of pesticides. Water with a pH of 7.0 to 8.5 will require more chlorine for the destruction of pathogens than will water that is slightly acidic (NDSU, 1987).

2.1.3 Electrical Conductivity

Electrical conductivity is the measure of the ability of water to conduct an electric current and depends upon the number of ions or charged particles in the water, and is measured by passing a current between two electrodes (a known distance apart) that are placed into a sample of water. The unit of measurement for electrical conductivity is expressed in either micro Siemens per centimetre (μS/cm) or milli Siemens per centimetre (mS/cm).

Electrical conductivity determinations are useful in aquatic studies because they provide a direct measurement of dissolved ionic matter in the water. Low values are characteristic of high-quality, low-nutrient waters. High values of conductance can be indicative of salinity problems but also are observed in eutrophic waterways where plant nutrients (fertiliser) are in greater abundance. Very high values are good indicators of possible polluted sites. A sudden change in electrical conductivity can indicate a direct discharge or other source of pollution into the water. However, electrical conductivity readings do not provide information on the specific ionic composition and concentrations in the water. (E. Boyd, 2000)

Low Conductivity (0 to 200 µS/cm) is an indicator of pristine or background conditions. Mid range conductivity (200 to 1000 µS/cm) is the normal background for most major rivers. Conductivity outside this range could indicate that the water is not suitable for certain species of fish or bugs. High conductivity (1000 to 10,000 µS/cm) is an indicator of saline conditions. Waters that have been heavily impacted by industry can fall into this range (NDSU, 1987).

2.1.4 Total Dissolved Solid

Total solids refer to the presence of materials suspended or dissolved in water and is related to both electrical conductivity and turbidity (Murphy, 2007). Total dissolved solids (TDS) are characterized mainly by major anions and actions such as carbonate, bicarbonate, sulfate, chloride, nitrate, sodium, calcium, magnesium, and potassium (NGL, 2002).

Total Solids includes both total suspended solids **(**TSS**),** the portion of total solids retained by a filter, and total dissolved solids **(**TDS**),** the portion that passes through a filter(Murphy,2007a). Concentrations above 500 ppm of TDS may cause adverse taste effects on drinking water **(**wells, 2000**).**

With respect to drinking water quality, water with extremely low TDS concentrations may be objectionable because of its flat, insipid taste. High concentration of TDS on the other hand causes some physiological problems (Lechevallier *et al.*, 1981). These may include: laxative effects mainly from sodium, sulfate and magnesium sulfate. The adverse effects of high concentration of sodium on certain cardiac patients and kidney function are well documented (ADWD, 2004).

2.1.5 Alkalinity

Alkalinity is defined as the capacity of water to accept H^+ ions (protons). It can also be defined as the capacity of water to neutralize acids whereas acidity is the capacity of water to neutralize bases. Major species responsible for alkalinity in water are bicarbonate, carbonate, and hydroxide ions. These ions are effective by removing protons from water as given below. Ammonia, borates, organic bases, phosphates, and silicates can also be minor contributors to alkalinity (E. Boyd, 2000).

$$H^+ + OH^- \leftrightarrow H_2O$$

$$H^+ + HCO_3^- \leftrightarrow H_2CO_3$$

$$H^+ + CO_3^{2-} \leftrightarrow HCO_3^-$$

Alkalinity in natural waters is usually due to the carbonate and bicarbonate salts of calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K). Among those, carbonate is the most important alkalinity sources in natural water. Limestone produces high amount of carbonate ions through dissolving in water while flowing through geology. Limestone is composed of calcium carbonate ($CaCO_3$) and/or dolomite ($CaMg(CO_3)_2$) mineral (E. Boyd, 2000).

Alkalinity is important in water treatment and in the chemistry and biology of natural waters. Highly alkaline water often has a high pH and generally contains elevated levels of dissolved solids. These characteristics may be detrimental for water to be used in boilers, food processing, and municipal water systems. Alkalinity is closely related to pH and alkalinity in water acts as a buffer that tends to stabilize and prevent fluctuations in pH. Without buffering capacity, any acid addition to water body would immediately change pH. Higher amount of acidity cause corrosion on pipes and alkalinity can protect water distribution system from the corrosive effects (NDSU, 1987).

Total alkalinity concentration for natural waters may range from 0 mg/l to more than 500 mg/l. The total alkalinity of water may be categorized by concentration as follows:(E. Boyd, 2000)

Less than 10 mg/l	very Low
10 – 50 mg/l	Low
50 – 150 mg/l	Moderate
150 – 300 mg/l	High
More than 300 mg/l	Very high

2.2 COLLOIDAL PARTICLES

Solids are present in water in three main forms: suspended particles, colloids, and dissolved molecules. Suspended particles, such as sand, vegetable matter and silts, range in size from very large particles down to particles with a typical dimension of 10 μm. Colloids are very fine particles, typically ranging from 10^{-5} mm to 10^{-6} mm. Materials smaller than approximately 10^{-6} mm are referred to as dissolved. Such material includes inorganic simple and complex ions, molecules and polymeric species, polyelectrolytes, organic molecules, undissociated solutes and small aggregates (MWH, 2012).

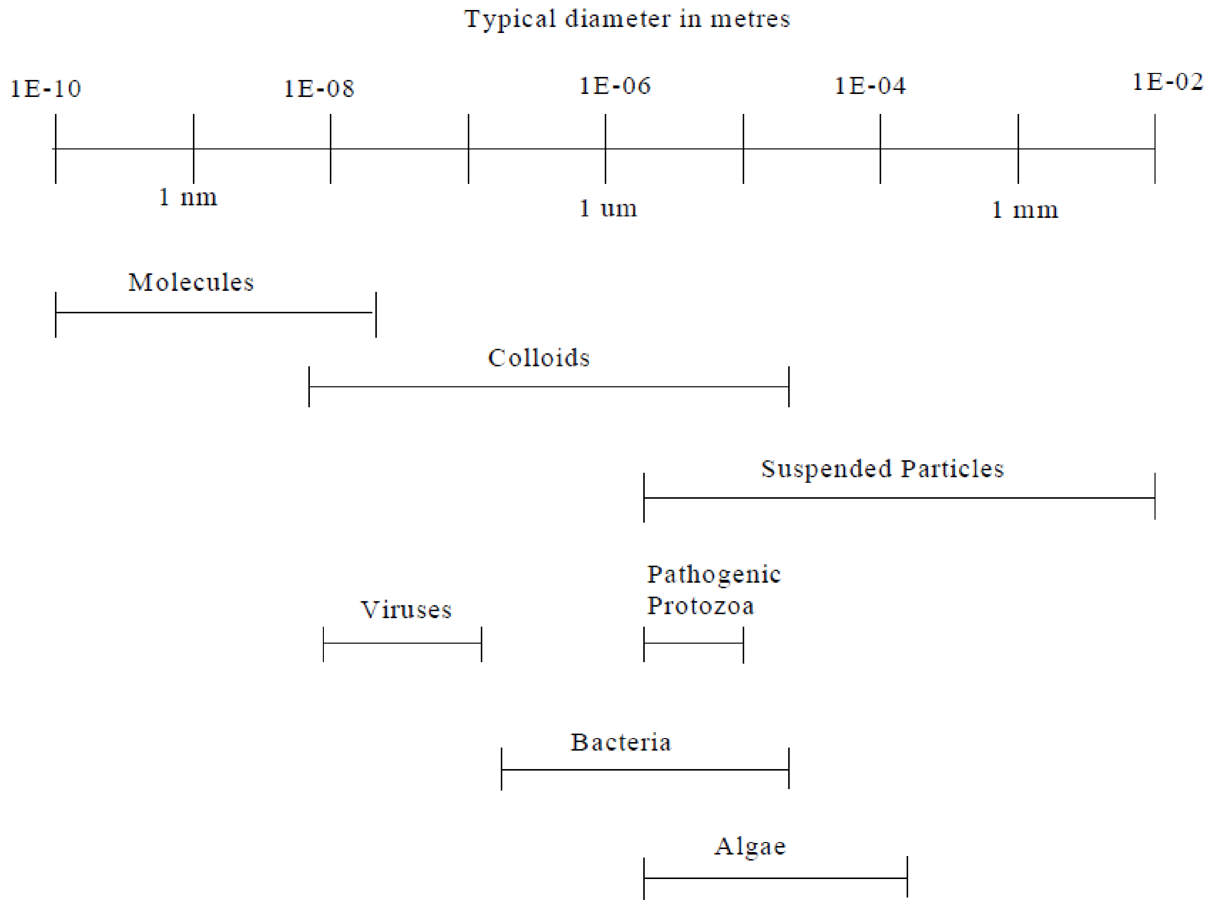


Figure 2.1 Size ranges of particles of concern in water treatment (Binnie et al. 2002)

Colloid is defined as a substance that consists of particles dispersed in throughout another substance which are too small for resolution with an ordinary light microscope but are incapable of passing through a semi permeable membrane (Webster, 2001). A more specific definition would be particles that are too small to settle out of suspension in water that will be used for human consumption. Colloidal materials include mineral substances, small aggregates of precipitated and flocculated matter, silt, bacteria, plankton, viruses, biopolymers and macromolecules.

Colloidal solids in water may be classified as hydrophilic or hydrophobic according to their affinity for water. Hydrophilic colloids have an affinity for water because of the existence of water-soluble groups on the colloidal surface. Some of the principal groups are the amino, carboxyl, sulfonic and hydroxyl. Since these groups are water-soluble they promote hydration and cause a water layer or film to collect and surround the hydrophilic colloid. Frequently, this water layer or film is termed the water of hydration or bound water. Usually organic colloids, such as protein and their degradation products are hydrophilic. Hydrophobic colloids have little, if any affinity for water: as a result, they do not have any significant water film or water of hydration. Usually inorganic colloids such as clays are hydrophobic (Reynolds, 1996).

Colloidal particles have electrostatic forces that are important in maintaining a dispersion of the colloid. The surface of a colloidal particle tends to acquire an electrostatic charge due to the ionization of surface group and the adsorption of ions from the surrounding solution. Also, colloidal minerals such as clay have an electrostatic charge due to the ionic deficit within the mineral lattice. Hydrophilic colloids, such as proteinaceous materials and microbes have charge due to the ionization of such groups as the amino ($-NH_2$) and the carboxyl (-COOH) which are located on the on the colloidal surface. When the PH is at the isoelectric point the net overall charge is zero since the amino group is ionized ($-NH_3^-$) and also the carboxyl group is ionized ($-COO^-$). At the PH below the isoelectric point, the carboxyl group is not ionized (-COOH), and the colloidal is positively charged as a result of the ionized amino group ($-NH_3^-$). At a PH above the isoelectric point, the amino group loses a hydrogen producing a neutral group ($-NH_2$) and the colloid is negatively charged because of the ionized carboxyl group ($-COO^-$) (Reynolds, 1996).

In general, most naturally hydrophilic colloids such as proteinaceous matter and microbes have a negative charge if the PH is at or above the neutral range. Some colloidal materials such as oil droplets and some other chemically inert substances will preferentially adsorb negative ions particularly the hydroxyl ion from their surrounding solution and become negatively charged. Colloidal minerals such as clay have more non metallic atoms than metallic atoms within their crystalline structure resulting in a net negative charge. Usually most naturally occurring hydrophobic colloids such as clays are inorganic materials and have a negative charge. The sign and magnitude of the charge of a colloid will depend on the type of colloidal matter and on the characteristics of the surrounding solution (Reynolds, 1996).

2.2.1 Stability of Colloids

In most colloidal systems the colloids are maintained in suspension (stabilized) as a result of the electrostatic forces of the colloids themselves. The term stability refers to the capacity of particles to remain as independent entities within a given dispersion. Since most naturally occurring colloids are negatively charged and like charges are repulsive, the colloids remain in suspension because of the action of the repulsive forces. (HBPWS, 2001)

It is due to the overriding influences of surface phenomena that colloids, which posses a colossal surface area to mass ratio, have the ability to exist as stable dispersion. For illustrative purpose, Table 2.1 presents the total surface area for an original particle of diameter 10 mm split into spheres of progressively smaller diameters. As the size of particles becomes progressively smaller, the total surface becomes extremely large for a given total particle mass. Hence it is apparent that for a given total mass, the smaller the particles the more predominant becomes the influence of phenomena associated with interfaces. Moreover, the lesser becomes the influences of gravity effect associated with mass. (Bartby, 2006)

Table 2.1 classification of particle sizes (Adapted from Bratby 2006)

Particle size mm	**Classification**	**Examples**	**Total surface area m^2/cm^3**	**Time required to settle 100mm** If specific gravity = 2.65
10 1 10^{-1}	Coarse dispersion (visible to naked eye)	Gravel, coarse sand, mineral substances, precipitated and flocculated particles, silt, macroplankton	6x 10-^{4} 6×10^{-3} 6×10^{-2}	0.1 s 1 s 13 s
10^{-2} 10^{-3} 10^{-4}	Fine particulate dispersion (visible under microscope)	Mineral substances, precipitated and flocculated particles, bacteria, plankton and other organisms	0.6 6 60	11 min 20 hrs 80 days
10^{-5} 10^{-6}	Colloidal dispersion (submicroscopic)	Mineral substances, hydrolysis and precipitated products , macromolecules, biopolymer, viruses	600 6000	2 years 20 years
$< 10^{-6}$	Solution	Inorganic simple and complex ions, molecules and polymeric species, Polyelectrolytes, organic molecules, undissociated solutes		

With particulate materials in the colloidal size range, it is apparent from Table 2.1 that Considering hydrodynamic effect alone time scale of up to several years may be required for colloidal materials to settle through a significant distance. Furthermore, because of a number of phenomena to which small particles are subjected, a change in position arising from gravity effect could in a statistical sense involve geological time spans. Such phenomena, which include thermal convection currents within the dispersion medium, and molecular and ionic bombardment, serve to maintain particles in effectively permanent suspension. (Bartby, 2006)

2.2.2 The Electric Double Layer

The double layer model is used to visualize the ionic environment in the vicinity of a charged colloid and explains how electrical repulsive forces occur. It is easier to understand this model as a sequence of steps that would take place around a single negative colloid if the ions surrounding it were suddenly stripped away. The concept of the electrical double layer was proposed initially by Helmholtz and later modified and improved by Gouy, Chapman, and Stern. (HBPWS, 2001)

The Helmholtz theory: A layer of positive ions covers the entire surface of the colloid and ensures the neutrality of the entire mass (bound layer).

The Gouy-Chapman theory: The layer of positive ions is spaced unevenly around the colloid; neutrality is obtained at a greater distance (diffuse layer).

The Stern theory: brings together the two preceding theories and introduces the idea of a double layer. The first layer, which is attached to the colloid, rapidly loses its potential. The second layer, which is more diffuse, undergoes a slower loss of potential.

The effect of the colloid on the positive ions, which are often called counter-ions. Initially, attraction from the negative colloid causes some of the positive ions to form a firmly attached layer around the surface of the colloid. This layer of counter-ions is known as the Stern layer. Additional positive ions are still attracted by the negative colloid but now they are repelled by the positive Stern layer as well as by other nearby positive ions that are also trying to approach the colloid. This constant attraction and repulsion results in the formation of a diffuse layer of charged ions surrounding the colloid and Stern layer (MWH, 2012).

The diffuse layer can be visualized as a charged atmosphere surrounding the colloid. At any distance from the surface, its charge density is equal to the difference in concentration of positive and negative ions at that point. Charge density is greatest near the colloid and rapidly diminishes towards zero as the concentration of positive and negative ions merge together. The attached counter-ions in the Stern layer and the charged atmosphere in the diffuse layer are what we refer to as the *double layer*.

The thickness of the double layer depends upon the concentration of ions in solution. A higher level of ions means more positive ions are available to neutralize the colloid. The result is a thinner double layer. Decreasing the ionic concentration (by dilution, for example) reduces the number of positive ions and a thicker double layer results. The type of counter-ion will also influence double layer thickness. Type refers to the valence of the positive counter-ion. For instance, an equal concentration of aluminum (Al^{+3}) ions will be much more effective than sodium (Na^{+}) ions in neutralizing the colloidal charge and will result in a thinner double layer. (MWH 2012)

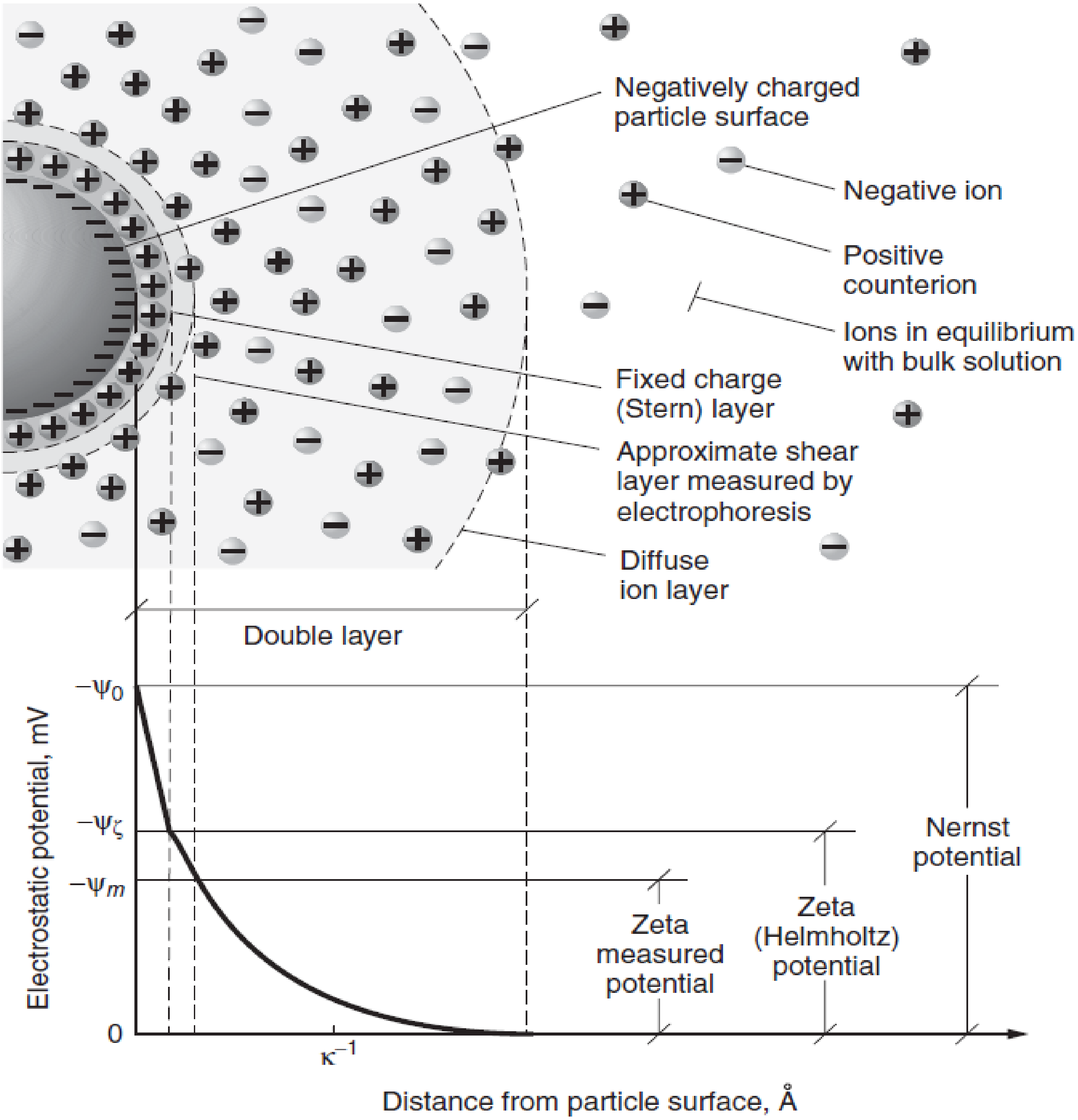


Figure 2.2 Structure of the electrical double layer. (Adapted from MWH 2012)

The DLVO Theory (for Derjaguin, Landau, Verwey and Overbeek) is the classic model which describes the balance of forces between charged colloid particles. Amirtharajah and O'Melia (1990) provide a thorough discussion of the electrostatic theory of colloidal stability from the DLVO model and other works.

When two similar colloidal particles with similar primary charge approach each other, their diffuse layers begin to interact. The similar primary charges they possess result in repulsive forces. The closer the particles approach, the stronger the repulsive forces. Repulsive forces which keep particles from aggregating are counteracted to some degree by an attractive force termed *van der Waals* attraction. All colloidal particles possess this attractive force regardless of charge and composition. As van der Waals forces tend to be relatively weak attractions, the force decreases rapidly with an increasing distance between particles. (HBPWS, 2001)

The balance of the two opposing forces, electrostatic repulsion and van der Waals attraction, explains why some colloidal systems agglomerate while others do not. As particles with similar charge approach one another, the repulsive electrostatic forces increase to keep them separated. However, if they can be brought sufficiently close together to get past this energy barrier, the attractive van der Waals force will predominate, and the particles will remain together. The random motion of colloids caused by the constant collisions with water molecules, termed Brownian movement, will bring particles in close proximity and aggregation may occur. However, the addition of coagulant and polymers is typically used to lower the energy barriers between particles and provide efficient agglomerations for settling. (HBPWS, 2001)

2.2.3 Zeta Potential

The Stern layer is considered to be rigidly attached to the colloid, while the diffuse layer is a dynamic layer of charged particles. The *Nernst Potential* is the measurement of voltage (in the order of millivolts) in the diffuse layer. The potential is a maximum at the Stern layer and drops exponentially through the diffuse layer. The z*eta potential* is the electrical potential representing the difference in voltage between the surface of the diffuse layer and the water. It is important to know the magnitude of the zeta potential, as it represents the strength of the repulsion between colloid particles and the distance which must be overcome to bring the particles together. (Reynolds, 1996)

The primary charge on a colloid cannot be measured directly. However, the zeta potential can be computed from measurements of particle movement within an electrical field (electrophoretic mobility). Therefore, the zeta potential, ζ, is defined by the equation:

$$\zeta = \frac{4\pi\delta q}{D}$$

where q = charge of the particle

δ = thickness of the zone of influence of the charge on the particle

D = dielectric constant of the liquid

The magnitude of the zeta potential is an approximate measure of colloidal particle stability. Low zeta potentials indicate relatively unstable systems (particles tend to coagulate), while a high zeta potential represents strong forces of separation (via electrostatic repulsion) and a stable system (particles tend to suspend). (MWH,2012)

2.3 COAGULATION OF COLLOIDS

Coagulation is the process of destabilization of colloids by adding chemicals (Coagulants) with a counter charge to neutralize the charge carried by the colloids. This will reduce the repelling force and gives the opportunity for the attractive forces to prevail and allow the particles and make them ready to agglomerate and form bigger particles. (HBPWS, 2001)

The aggregation of these suspended colloidal particles takes place in two separate and distinct phases. First, the repulsion force between particles must be overcome, a step that requires that the particles be destabilized; and, second, contact between the destabilized particles must be induced so that aggregation can occur. The destabilization step typically is achieved through the addition of chemicals to modify the electrochemistry properties on the particle surfaces, followed by thorough blending in rapid mix tanks. The aggregation step is accomplished through gentle stirring (slow mixing) in flocculation tanks.

2.3.1 Coagulation Mechanisms

Coagulation can be accomplished through any of four different mechanisms:

- Double-layer compression.
- Adsorption and charge neutralization.
- Enmeshment by a precipitate (sweep-floc coagulation).
- Adsorption and interparticle bridging.

Double-layer compression - The classical method of colloid destabilization is double-layer compression. To affect double-layer compression, a simple electrolyte such as NaCl is added to the suspension. The ions that are opposite in sign to the net charge on the surface of the particles enter the diffuse layer surrounding the particle. If enough of these counterions are added, the diffuse layer is compressed, reducing the energy required to move two particles of like surface charge into close contact. Destabilization by double-layer compression is not a practical method for water treatment because the salt concentrations required for destabilization may approach that of seawater and, in any case, the rate of particle aggregation would still be relatively slow in all but the most concentrated suspensions. Double-layer compression, however, is an important destabilization mechanism in certain natural systems, for example, estuaries (Edzwald et al., 1974).

Adsorption and charge neutralization - Destabilization by surface charge neutralization involves reducing the net surface charge of the particles in the suspension. As the net surface charge is decreased the thickness of the diffuse layer surrounding the particles is reduced and the energy required to move the particles into contact is minimized. Two processes are used to accomplish surface charge neutralization. In the first, coagulant compounds that carry a charge opposite in sign to the net surface charge of the particles are adsorbed on the particle surface. (In some cases the coagulant is a small particle that deposits on the particle surface.) The coagulants used to accomplish this usually have a strong tendency to adsorb on (attach to) surfaces. Examples include the synthetic and natural organic polyelectrolytes and some of the hydrolysis products formed from hydrolyzing metal salt coagulants. The tendency for these compounds to adsorb is usually attributable to both poor coagulant-solvent interaction and a chemical affinity of the coagulant or chemical groups on the coagulant for the particle surface. Most of the coagulants that are used for charge neutralization can adsorb on the surface to the point that the net surface charge is reversed and, in some cases, increased to the point that the suspension is restabilized (MWH, 2012).

Enmeshment by a precipitate (sweep-floc coagulation) - The addition of certain metal salts, oxides, or hydroxides to water in high dosages could result in the rapid formation of precipitates. These precipitates enmesh the suspended colloidal particles as they settle. Coagulants such as aluminum sulfate ($Al_2(SO_4)_3$), ferric chloride ($FeCl_3$), and lime CaO or $Ca(OH)_2$) are frequently used as coagulants to form the precipitates of $Al(OH)_3(s)$, $Fe(OH)_3(s)$ and $CaCO_3(s)$. The removal of colloids by this method has been termed *sweep-floc coagulation*.

This process can be enhanced when the colloidal particles themselves serve as nuclei for the formation of the precipitate. Therefore, the rate of precipitation increases with an increasing concentration of colloidal particles (turbidity) in the solution. Sometimes additional turbidity (e.g., bentonite particles) is artificially added to the raw water to enhance the sweep-floc coagulation. Packham reported the inverse relationship between the optimum coagulant dose and the concentration of the colloids to be removed. Benefield explained this phenomenon as follows:

At low colloidal concentrations, a large excess of coagulant is required to produce a large amount of precipitate that will enmesh the relatively few colloidal particles as it settles.
At high colloidal concentrations, coagulation will occur at a lower chemical dosage because the colloids serve as nuclei to enhance precipitate formation.

This method of coagulation does not depend upon charge neutralization, so an optimum coagulant dose does not necessarily correspond to minimum zeta potential. However, an optimum pH does exist for each coagulant. (HBPWS, 2001)

Adsorption by Interparticle Bridging - Destabilization by bridging occurs when segments of a high-molecular-weight polymer adsorb on more than one particle, thereby linking the particles together. When a polymer molecule comes into contact with a colloidal particle, some of the reactive groups on the polymer adsorb on the particle surface and other portions extend into the solution. If a second particle with open surface is able to adsorb the extended molecule, then the polymer will have formed an interparticle bridge. The polymer molecule must be long enough to extend beyond the electrical double layer (to minimize double-layer repulsion when the particles approach) and the attaching particle must have available surface. The adsorption of excess polymer may lead to restabilization of the suspension. Ions such as calcium are known to affect the bridging process, apparently by linking sites on interacting polymer chains (Black et al., 1965; Lyklema, 1978; Dentel, 1991).

The chemical bridging theory, shown schematically in Figure 2.3, may be explained as follows. The simplest form of bridging, shown in Figure 2.3a, proposes that a polymer molecule will attach to a colloidal particle at one or more sites. Colloidal attachment is postulated to occur as a result of coulombic attraction if the charges are of opposite charge or from ion exchange, hydrogen bonding, or van der Waal’s forces. The second reaction is shown in Figure 2.3b, where the remaining length of the polymer molecule from the first reaction extends out into the bulk of the solution. If a second particle having some vacant adsorption sites contacts the extended polymer, attachment can occur to form a chemical bridge. The polymer then serves as the bridge. However, if the extended polymer molecule does not contact another particle, it can fold back on itself and adsorb on the remaining sites of the original particle, as shown in Figure 2.3c. In this event, the polymer is no longer capable of serving as a bridge, and in fact it restabilizes the original particle. (HBPWS, 2001)

Colloidal restabilization can occur from an overdose of polymer to the sol or from extended or intense agitation. If polymer is added in excess quantities, the polymer segments may saturate the colloidal surfaces to the extent that no sites are available for interparticle bridging. This reaction, shown in Figure 2.3d, results in restabilization of the particles. Excess organic polymer may also increase TOC in the treated water or foul the downstream filters. Intense or extended agitation can result in restabilization due to the destruction of previously formed polymer-surface bonds or bridges. These reactions are depicted in Figures 2.3e and 2.3f. (HBPWS, 2001)

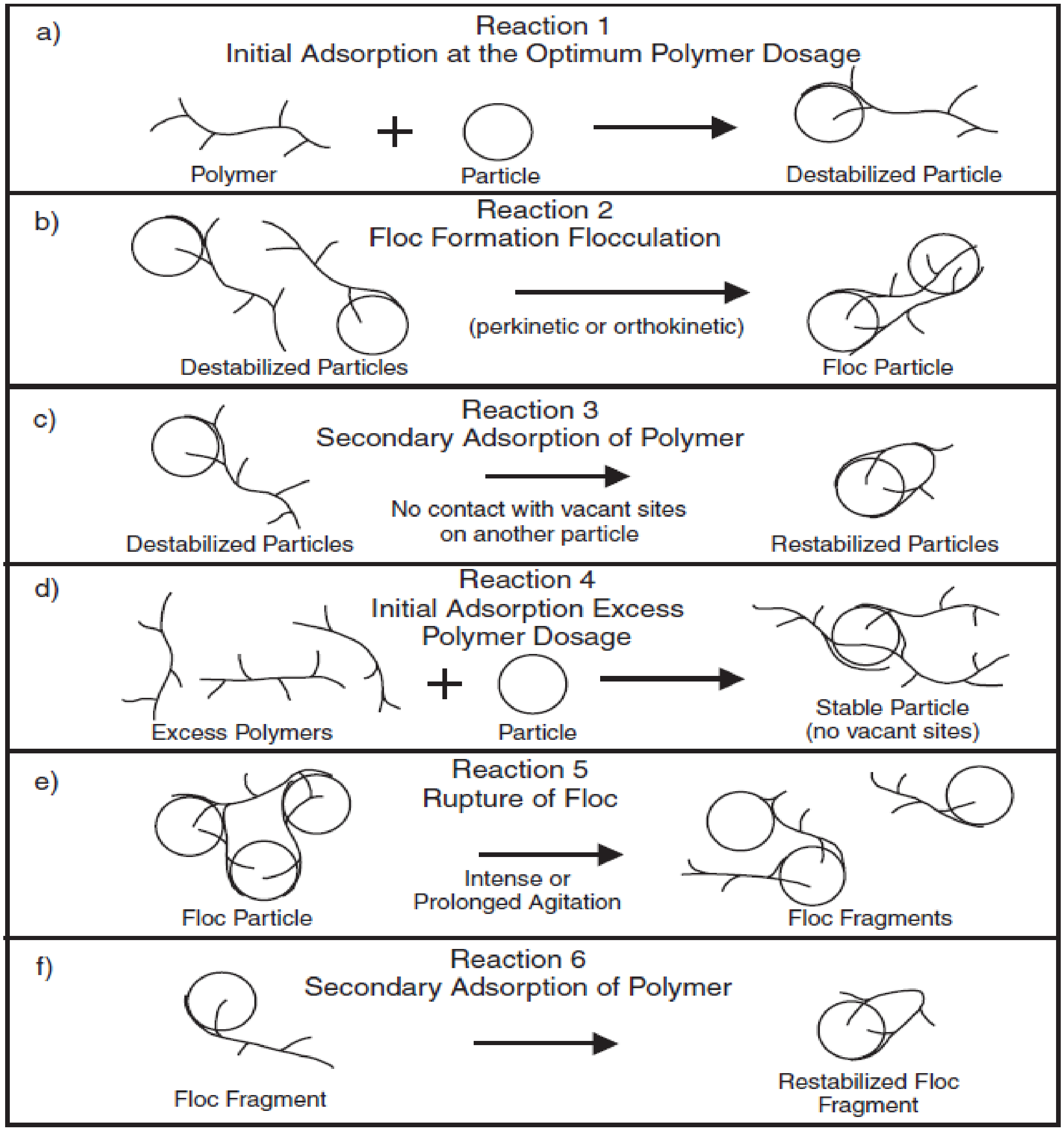


Figure 2.3 Schematic representation of the bridging model for the destabilization of colloids by polymers (Adapted from HBWS, 2001)

2.4 CHEMICAL COAGULANTS

Chemicals used in coagulation/flocculation are referred to either as primary coagulants or as coagulant aids. Primary coagulants are used to cause the particles to become destabilized and begin to clump together. The purpose of coagulant aids may be to condition the water for the primary coagulant being used, to add density to slow-settling flocs or toughness so the floc will not break up in the following processes.

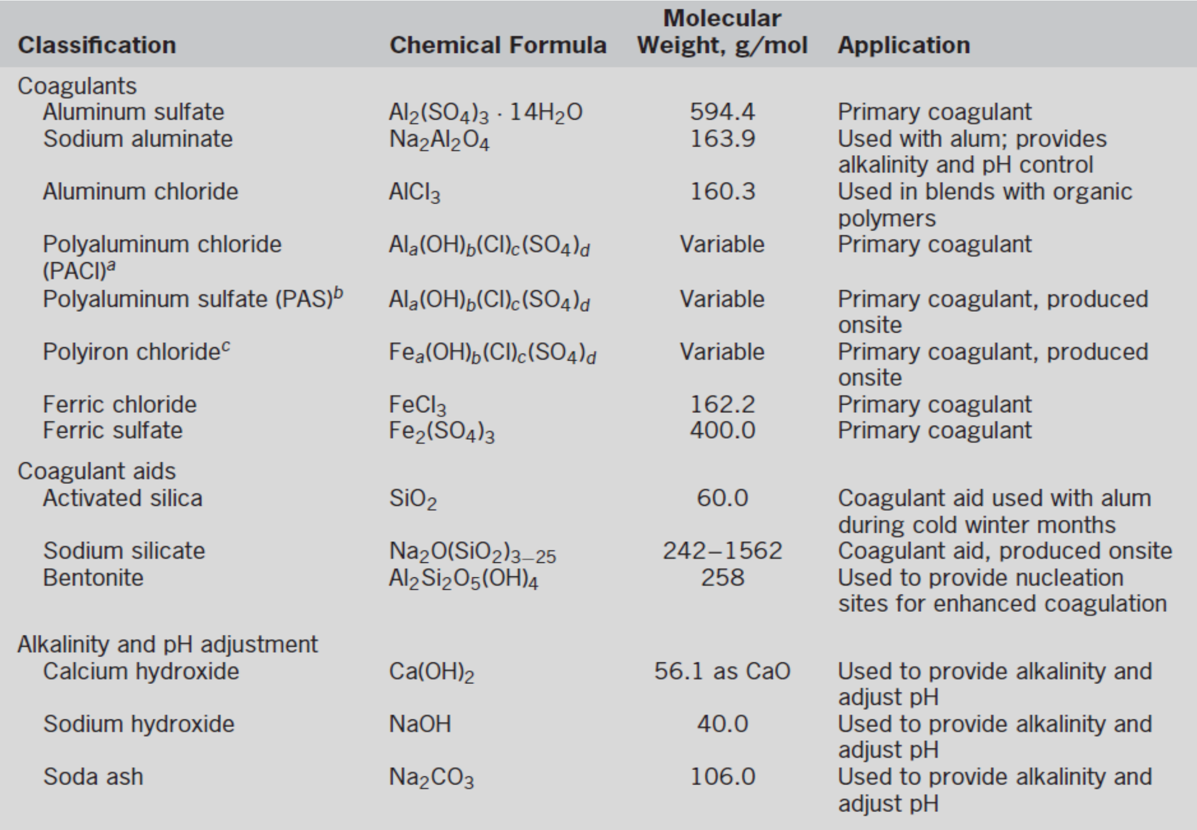
Many coagulants are used in water treatment process for turbidity removal. Theses coagulants can be classified into three types which are inorganic coagulants, synthetic organic polymer and natural coagulants.

2.4.1 Metal Coagulants

The commonly used metal coagulants fall into two general categories: those based on aluminum and those based on iron. The aluminum coagulants include aluminum sulfate, aluminum chloride, polyaluminum chloride and sodium aluminate. The iron coagulants include ferric sulfate, ferrous sulfate, ferric chloride, polyferric sulfate and ferric salts with organic polymers. Other metals used as coagulants include hydrated lime and magnesium carbonate (Bratby, 2006).

The popularity of aluminum and iron coagulants arises not only from their effectiveness as coagulants, but also from their ready availability and relatively lower cost. The efficiency of these coagulants arises principally from their ability to form multi charged poly nuclear complexes in solution with enhanced adsorption characteristics (Bratby, 2006).

Table 2.2 Common inorganic coagulants, coagulant aids, and pH and alkalinity adjusting chemicals used in water treatment (Adapted from MWH 2012)



Classification	Chemical Formula	Molecular Weight, g/mol	Application
Coagulants			
Aluminum sulfate	$Al_2(SO_4)_3 \cdot 14H_2O$	594.4	Primary coagulant
Sodium aluminate	$Na_2Al_2O_4$	163.9	Used with alum; provides alkalinity and pH control
Aluminum chloride	$AlCl_3$	160.3	Used in blends with organic polymers
Polyaluminum chloride (PACl)[a]	$Al_a(OH)_b(Cl)_c(SO_4)_d$	Variable	Primary coagulant
Polyaluminum sulfate (PAS)[b]	$Al_a(OH)_b(Cl)_c(SO_4)_d$	Variable	Primary coagulant, produced onsite
Polyiron chloride[c]	$Fe_a(OH)_b(Cl)_c(SO_4)_d$	Variable	Primary coagulant, produced onsite
Ferric chloride	$FeCl_3$	162.2	Primary coagulant
Ferric sulfate	$Fe_2(SO_4)_3$	400.0	Primary coagulant
Coagulant aids			
Activated silica	SiO_2	60.0	Coagulant aid used with alum during cold winter months
Sodium silicate	$Na_2O(SiO_2)_{3-25}$	242–1562	Coagulant aid, produced onsite
Bentonite	$Al_2Si_2O_5(OH)_4$	258	Used to provide nucleation sites for enhanced coagulation
Alkalinity and pH adjustment			
Calcium hydroxide	$Ca(OH)_2$	56.1 as CaO	Used to provide alkalinity and adjust pH
Sodium hydroxide	$NaOH$	40.0	Used to provide alkalinity and adjust pH
Soda ash	Na_2CO_3	106.0	Used to provide alkalinity and adjust pH

Coagulation Using Al (III) and Fe (III)

When ferric or aluminum ions are added to water, a number of parallel and sequential reactions occur. Initially, when a salt of Al (III) and Fe (III) is added to water, it will dissociate to yield trivalent Al^{3+} and Fe^{3+} ions, as given below:

$$Al_2(SO_4)_3 \leftrightarrow 2Al^{3+} + 3SO4^{2-} \qquad (2.2)$$

$$FeCl_3 \leftrightarrow Fe^{3+} + 3Cl^{-} \qquad (2.3)$$

The trivalent ions of Al^{3+} and Fe^{3+} then hydrate to form the aquometal complexes $Al(H_2O)_6^{3+}$ and $Fe(H_2O)_6^{3+}$, as shown on the left-hand side of Eq. 2.4. As shown, the metal ion (aluminum in this case) has a coordination number of 6 and six water molecules orient themselves around the metal ion. (MWH, 2012)

$$\begin{bmatrix} H_2O & & OH_2 \\ H_2O - Al - OH_2 \\ H_2O & & OH_2 \end{bmatrix}^{3+} \leftrightarrow \begin{bmatrix} H_2O & & OH_2 \\ H_2O - Al - OH_2 \\ H_2O & & OH_2 \end{bmatrix}^{2+} + H^+ \qquad (2.4)$$

These aquometal complexes then pass through a series of hydrolytic reactions, as illustrated on the right-hand side of Eq. 2.7, which give rise to the formation of a variety of soluble mononuclear (one aluminum ion) and polynuclear (several aluminum ions) species, as illustrated on Fig. 2.4. The mononuclear species $Al(H_2O)_5(OH)^{2+}$ [or just $Al(OH)^{2+}$] and $Al(H_2O)_4(OH)^{2+}$ [or just $Al(OH)^{2+}$] are among the many species formed. Similarly, iron forms a variety of soluble species, including mononuclear species (one iron ion) such as $Fe(H_2O)_5(OH)^{2+}$ [or just $Fe(OH)^{2+}$] and $Fe(H_2O)_4(OH)^{2+}$ [or just $Fe(OH)^{2+}$]. (HBPWS, 2001)

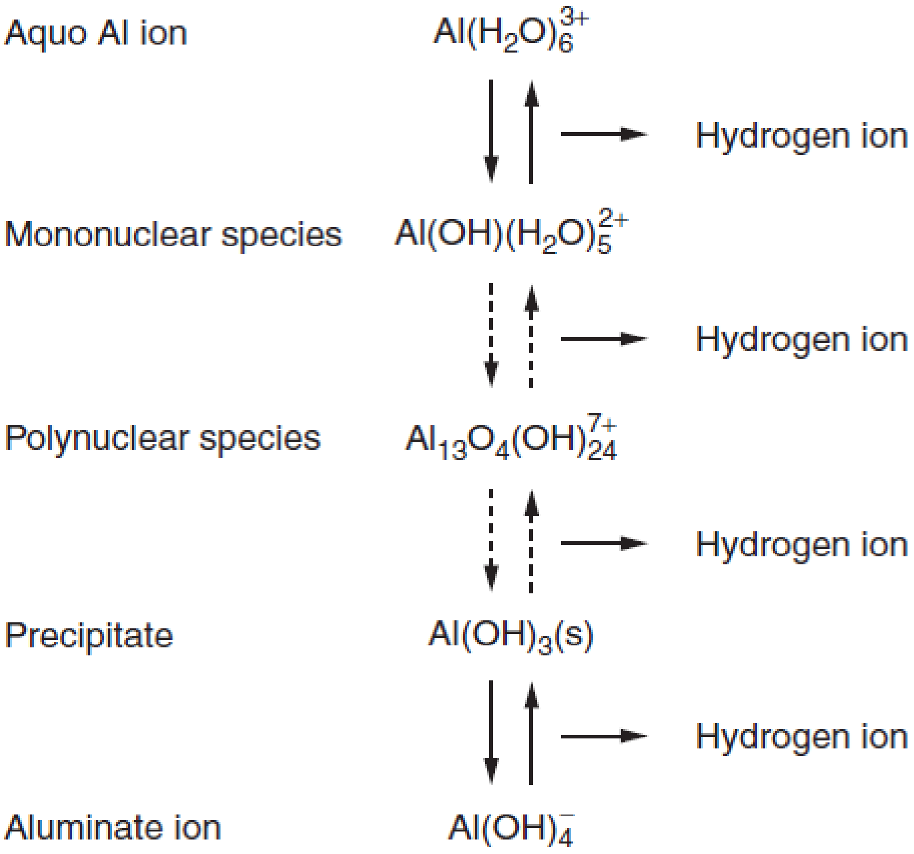
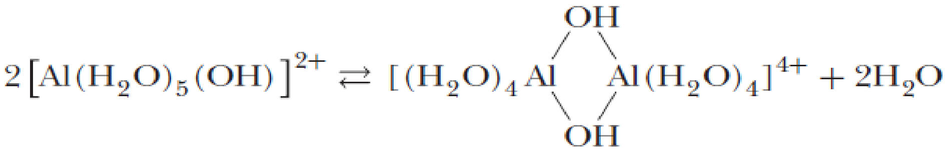


Figure 2.4 Aluminum hydrolysis products. The dashed lines are used to denote an unknown sequence of reactions. (Adapted from Letterman, 1981)

$$Al(H_2O)_6^{+3} + H_2O = Al(H_2O)_5(OH)^{-2} + H_3O^+ \qquad (2.5)$$

$$Fe(H_2O)_6^{+3} + H_2O = Fe(H_2O)_5(OH)^{+2} + H_3O^+ \qquad (2.6)$$

Polynuclear species such as $Al_{18}(OH)_{20}{}^{4+}$ form via hydroxyl bridges. For example, a hydroxyl bridge for two aluminum atoms is shown below:



$$2\left[Al(H_2O)_5(OH)\right]^{2+} \rightleftarrows [(H_2O)_4Al(OH)_2Al(H_2O)_4]^{4+} + 2H_2O \qquad (2.7)$$

The speciation of metal complexes or hydroxides greatly depends on the pH of the solution. When Al(III) or Fe(III) salts are added to water in quantities less than the solubility limit of the hydroxide, the hydrolysis products will form and will adsorb on the colloidal particles. Adsorption of the hydrolysis products will cause destabilization by charge neutralization. However, when the amount of Al(III) or Fe(III) added to the water exceeds the solubility limit of the hydroxide, the hydrolysis products will form as kinetic intermediates in the eventual precipitation of metal hydroxides. In this case, charge neutralization and enmeshment in the precipitate both act to destabilize and coagulate the colloids. (HBPWS, 2001)

Since the solubility of both iron and alumina is very low (less than 10^{-8} M) at the pH commonly used in water treatment (pH 6 −8), the amount of Al(III) or Fe(III) added in a conventional water coagulation process is sufficient to exceed the solubility limit of the respective metal hydroxides. The solubility of $Al(OH)_3(s)$ and $Fe(OH)_3(s)$ is a minimum at a specific pH (around pH 8.2 and pH 5.5 for Fe and Al, respectively) and increases as the pH increases or decreases from that point. Precipitation of amorphous metal hydroxides is necessary for sweep-floc coagulation. (MWH, 2012)

The pH must be controlled to establish optimum conditions for coagulation. For pHs below the isoelectric point of the metal hydroxide, positively charged polymers (kinetic intermediates) will be formed. Adsorption of these positive polymers can destabilize negatively charged colloids by charge neutralization. Above the isoelectric point, negative polymers will predominate and destabilization is achieved by bridge formation. Control of the coagulation process is complicated by the release of hydrogen ions as shown by Equations 2.5 through 2.6. The hydrogen ions liberated will react with the alkalinity in the water to yield (HBPWS, 2001):

$$Al_2(SO_4)_3 . 14H_2O + 3Ca(OH)_2 = 2Al(OH)_3 + 3CaSO_4 + 14H_2O + 6CO_2 \qquad (2.8)$$

Equation 2.8 predicts that each mg/L of alum will consume 0.50 mg/L (as $CaCO_3$) of alkalinity. If the alkalinity is not sufficient to react with the alum and buffer the pH, then it is necessary to add alkalinity to the water in the form of lime, sodium bicarbonate, soda ash, or some other similar chemical. The following are the stoichiometric reactions:

$$Al_2(SO_4)_3 . 14H_2O + 3Ca(OH)_2 = 2Al(OH)_3 + 3CaSO_4 + 14H_2O \qquad (2.9)$$

$$Al_2(SO_4)_3 . 14H_2O + 3Na_2CO_3 + 3H_2O = 2Al(OH)_3 + 3Na_2SO_4 + 3CO_2 + 14H_2O \quad (2.10)$$

As the Al(III) or Fe(III) is gradually added to water, low coagulant doses may not be sufficient to destabilize the colloidal particles. As the coagulant dosage increases, particles are destabilized and then rapid aggregation occurs. Increasing the coagulant dose further can cause restabilization of the dispersion at some pHs. Finally, if a sufficient quantity of coagulant is added, large amounts of metal hydroxide are precipitated that enmesh the colloidal particles and sweep-floc coagulation occurs.

A knowledge of the interrelationships between optimum coagulant dosage, pH, and colloid concentrations, combined with an understanding of the two modes of destabilization that are caused through the addition of Al(III) or Fe(III) salts, is useful in the operation of a coagulation process. O'Melia describes four types of suspension, as follows: (HBPWS, 2001)

- High colloid concentration, low alkalinity. This is the easiest system to treat, in that only one chemical parameter must be determined—the optimum coagulant dosage. Destabilization is achieved by adsorption of positively charged hydroxometal polymers; these are produced at acidic pH levels (pH 4 to 6, depending on the coagulant).

- High colloid concentration, high alkalinity. In this case, destabilization is again achieved by adsorption and charge neutralization at neutral and acidic pH levels. Because of the high alkalinity, the pH will generally remain in the neutral region where the hydroxometal polymers are not highly charged so that charge neutralization is more difficult. The engineer can elect to use a high coagulant dosage. Alternatively, it is possible to reduce alkalinity by adding acids so that particles can be destabilized with a lower coagulant dosage at a lower pH.

- Low colloid concentration, high alkalinity. Coagulation is readily accomplished here with a relatively high coagulant dosage by enmeshment of colloidal particles in a sweep floc. Alternatively, a coagulant aid (such as bentonite or clay particles) may be added to increase the colloid concentration and increase the rate of interparticle collision. Destabilization by adsorption and charge neutralization may then be effective at a lower primary coagulant dosage.

- Low colloid concentration, low alkalinity. Coagulation is most difficult in such systems. Al(III) and Fe(III) salts will be ineffective if used alone, because the pH will be depressed too low to permit the rapid formation of a sweep floc and the rate of interparticle contacts is presumably too slow to utilize destabilization by charge neutralization. Additional alkalinity, colloidal particles, or both must be added to provide effective coagulation.

2.4.2 Polymers

Synthetic organic polymers have been shown to be effective as coagulants or coagulant aids. Polymers are long-chain molecules composed of many subunits called monomers. A polymer that is composed of only one type of monomer is termed a homopolymer and those comprised of different monomers are termed copolymers. The number and type of subunits or monomers can be varied to yield a wide range of polymers having different chemical characteristics (such as charge polarity and charge density) and molecular weights (Bratby, 2006).

A polymer is called a polyelectrolyte if its monomers consist of ionizable groups. Polyelectrolytes having a positive charge upon ionization are referred to as cationic polymers. Negatively charged polyelectrolytes are termed anionic polymers. Finally, polymers that do not contain ionizable groups are called nonionic polymers. Cationic polymers can be effective in coagulating negatively charged clay particles. It has been hypothesized that electrostatic forces or ion exchange is the process by which the polymers become attached to the clay particles, which is then followed by bridging. Cationic polymers do not require a large molecular weight to be effective in destabilization. PolyDADMAC and EPI-DMA polymers are known to be the most widely used polymers worldwide, and reports suggest that they form 80% of polymers sold to the drinking water industry in the USA (Faust, 2010).

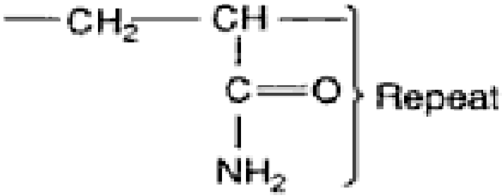
Anionic particles generally are ineffective coagulants for negatively charged particles, and there is strong evidence that the presence of divalent metal ions (such as Mg^{2+}) is necessary for anionic polymers to flocculate negative colloids. However, anionic polymers of large molecular weight or size are able to bridge the energy barrier between two negatively charged particles, thereby effectively enhancing the coagulation efficiency. The minimum polymer size depends on several factors, but limited data indicate that the minimum size is on the order of a molecular weight of one million. When anionic polymers are used in conjunction with an electrolyte such as NaCl or $CaCl_2$ or another coagulant such as alum, their coagulation efficiency is increased (Faust, 2010).

Low dosages of cationic polymer (0.1 to 1.5 mg/L) are usually sufficient to achieve coagulation. In contrast, 5 to 150 mg/L of alum is often needed to obtain similar results. Other important differences between the use of polymers and metal ions are sludge quantities and dosage control. The use of alum or ferric chloride can result in copious volumes of sludge that must be handled, whereas the additional sludge quantity is negligible when a polymer is used. A narrow bank exists for optimum polymer dosage. Overdosing or underdosing from this optimum will result in restabilization of the colloids. The control method for polymer feed systems must be precise and reliable to give satisfactory performance. (Faust, 2010)

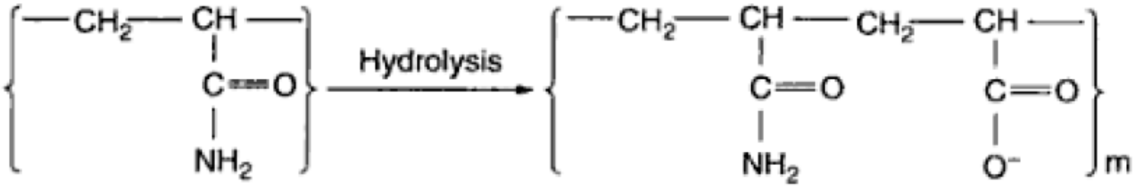
Because polymers do not affect the pH of water, their use offers a clear advantage for treating low-alkalinity waters. This is particularly true of the low-alkalinity waters that are high in turbidity. Such waters would require considerable quantities of alum, which would require the addition of soda ash or lime to replenish the buffering capacity of the water and maintain desirable pH (Bratby, 2006).

2.4.2.1 Structure of synthetic Polyelectrolytes

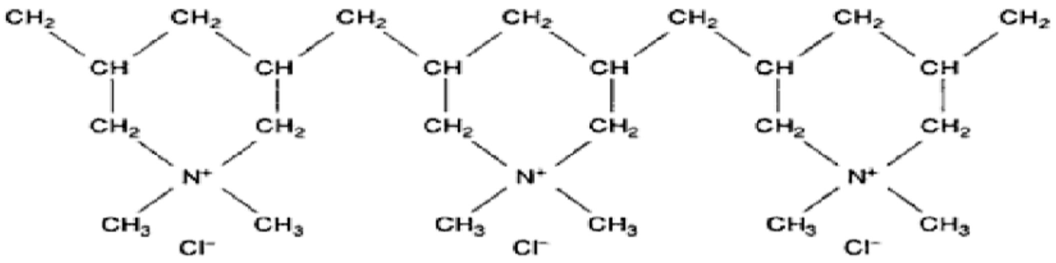
Many synthetic polyelectrolytes are based on polyacrylamide and its copolymers with polyacrylic acid. The acrylamide monomers, making up the units of the polymer, is prepared by reacting natural gas and methane at high temperatures in the presence of controlled amounts of oxygen and ammonia to form hydrocyanic acid and acetylene, followed by catalysis with cuprous chloride. The acrylonitrile that results is then acid-hydrolyzed to the acrylamide monomer using sulfuric acid. The acrylamide is then polymerized by catalysis. Polyacrylamide itself is nonionic but on hydrolysis the macromolecule acquires carboxyl groups and assumes an anionic character. The structure of nonionic Polyacrylamide is as follows (Bratby, 2006).



The structure of anionic hydrolyzed polyacrylamide is as follows:



Cationic derivative of polyacrylamide are also available. For example, those produced by postreaction of polyacrylamide with formaldehyde and dimethylamine – known as *Mannich* polymers. A common cationic quaternary ammonium compound is polydiallyldimethyl ammonium chloride (PDADMAC) which has the following structure (Bratby, 2006).



The polyDADMAC polymers are the most widely used polymers for potable water purification. They are well known to be the most chlorine resistant and operate over a wide pH range. Molecular weight of this polymer is typically 2 to 3 X 10^6 Daltons. PolyDADMAC polymers tend to have more unreacted monomer content than other polyelectrolyte products (Bratby, 2006).

2.4.2.2 Toxicity of synthetic polyelectrolytes

Contaminants of synthetic polymers used in water and wastewater treatment generally arise from residual unreacted monomers, unreacted chemicals used to produce the monomer units and reaction by-products of the polymers in water. Because of this concern, Switzerland and Japan do not permit the use of polyelectroytes in water treatment. (Faust, 2010)

With synthetic products, although there is no evidence that polymerized species are of high toxicity (Packham 1967), the unpolymerized monomer species are. For example, acrylamide is extremely toxic producing severe neurotoxic effects. Packham (1967) reports on experiments carried out on rats, guinea pigs, rabbits, cats and monkeys, where it was demonstrated that ingestion of acrylamide had the following progressive effects: stiffness and weakness of hindquarters; loss of ability to control hindquarters; urinary retention; ataxia of front legs and inability to stand (Bratby 2006).

Acrylamide is a commulative neurotoxin. When the total acrylamide dose reaches 100 to 150 mg/kg body weight, over short or long term exposure, neurotoxic effect begin to appear in many species. Neurotoxic effects in humans exposed to acrylamide in drinking water have also been reported (Letterman and pero 1990). The carcinogenicity of acrylamide, particularly affecting the thyroid, mammary and adrenal glands, as well as scrotum and oral cavity has been demonstrated in experimental animals (Bratby 2006).

Polymers added to chlorinated waters often result in a reduction in the effectiveness of the polymer due to degradation by chlorine. Another effect is the formation of disinfection by products. Chlorination of waters containing acrylamide produce chloroform ($CHCL_3$) and 2,3-dichloropropionic acid (Aizawa et al. 1990). The formation of N-nitrosodimethylamine (NDMA) by chlorination of waters treated with PDADMAC cationic polymer is also a concern (wileazak, 2003).

2.4.3 Coagulant Aids

Ideally, flocculated colloidal particles should settle rapidly and be strong enough to resist shearing forces. Often, the flocs do not possess these characteristics, and a coagulant aid is then added to improve floc properties. Coagulant aids that have been used include clays, activated silica, and polymers (Faust, 2010).

Bentonite clays have been used as coagulant aids for low-turbidity waters. The use of clay may reduce the amount of coagulant and improve the floc settleability. The reduction in required coagulant dose is achieved by providing greater particle contact opportunities (increased colloid concentration) with subsequent charge neutralization.

The other advantage of using clays is that the floc particles are weighted (ballasted) by the clay particles, which cause the floc to settle more rapidly than regular alum flocs. Bentonite doses in the range of 10 to 50 mg/L are generally sufficient for improved coagulation efficiency. However, the optimal dosage should be determined by laboratory testing (HBPWS, 2001).

Activated silica has also been used as a coagulant aid in water treatment plants. When used in conjunction with alum, activated silica, with a mechanism similar to that of bentonite particles, increases the rate of flocculation, improves floc toughness, and increases settleability (Kalibbala, 2007).

Activated silica normally is used with alum, with the dose typically in the range of 7 to 11 percent of the alum dose. However, use of excess silica can be detrimental to coagulation. Activated silica has been successfully added both before and after alum addition, although the latter approach is the more widely used. Jar tests should be used to identify the optimum combination of chemicals to use. Activated silica has also been found to be an effective filter aid because it strengthens the flocs (Gregory *et al*., 1997).

Both anionic and nonionic polymers have proved effective as coagulant aids. The polymers help to promote large floc particles by a bridging mechanism, after the colloidal particles have been destabilized by a coagulant such as alum. Nonionic polymers are more effective with increasing concentrations of divalent cations (Ca^{+2}, Mg^{+2}, etc.).

Anionic polymer doses in the range of 0.1 to 0.5 mg/L in association with primary metal-based coagulants improve floc settleability and toughness compared to primary coagulants alone. However, overdosing the solution can inhibit coagulation and should be avoided. A side benefit of using a combination of alum and polymer is the fact that frequently the coagulant dosage can be reduced and less sludge is produced.

2.5 FLOCCULATION

The purpose of the flocculation process is to promote the interaction of particles and form aggregates that can be efficiently removed in subsequent separation processes such as sedimentation, flotation, and coarse bed filtration. For efficient flocculation to occur, the suspension must be destabilized. This is usually accomplished by the addition of a coagulant (Faust, 2010).

There are two stages in the flocculation process; The first given the name perikinetic flocculation arise from thermal agitation (Brownian movement) and is a naturally random process. Flocculation during this stage commences immediately after destabilization and is complete within seconds, since there is a limiting floc size beyond which Brownian motion has no or little effect (Bratby, 2006).

Furthermore, although the potential energy barrier existing between colloidal particles may be overcomed by the thermal kinetic energy of Brownian movement, as the particles progressively coalesce, the magnitude of the energy barrier increases approximately proportional to the area of the floc, so that eventually perikinetic flocculation of such potentially repellent particles must cease (Bratby, 2006).

The rate of flocculation decrease in the particles of a suspension due to perikinetic flocculation may be described by a second order rate law. For example, in a turbid water containing 10^6 particles/ml, the particle number concentration would be reduced by half within a period of about 6 days, provided all the particles were completely destabilized and the particles did not become too large and be outside the range of Brownian movement (Bratby, 2006).

The second stage in the flocculation process is given the name orthokinetic flocculation and it arises from induced velocity gradients in the liquid. Such velocity gradient may be induced by setting the liquid in motion by (a) passage around baffles or mechanical agitation within a flocculation reactor; (b) the tortuous path through interstices of a granular filter bed; (c) by differential settlement velocities within a settling basin, and so on. The effect of velocity gradients within a body of liquid is to set up relative velocities between particles, thereby providing opportunity for contact. (Bratby, 2006)

For a given flocculating system, the principal parameter governing the rate of orthokinetic flocculation is the velocity gradient applied. The degree or extent of flocculation is governed by both applied velocity gradients and the time of flocculation. These two parameters influence the rate and extent of particle aggregation and the rate and extent of breakup of these aggregates. (Faust, 2010)

2.6 FACTORS AFFECTING COAGULATION/FLOCCULATION

Coagulation and flocculation processes are dependent on numerous inter-related factors, which sometimes make optimization of the processes cumbersome. Such factors include the characteristics of the water source, raw water pH, alkalinity and temperature, the type of coagulant and coagulant aids and their order of addition, dose rates of coagulants, the degree and time of mixing provided for chemical dispersion and floc formation. For water with low alkalinity coagulant can consume virtually all of the available alkalinity, hence lowering the pH to a level that hinders effective treatment, while high alkaline waters may require additional chemicals to lower the pH to values favorable for coagulation (Rossi and Ward, 1993; Kalibbala, 2007).

The performance of the hydrolysing metal salts is significantly influenced by the pH of the solution and they have a good coagulation effect within a certain pH range of the water. The coagulation process in water treatment can be modified to facilitate the removal of dissolved organic matter which has been reported to occur optimally at pH 5-6 and at maximum rate at pH 4 (Gregory and Duan, 2001).

Low temperature affects the coagulation and flocculation process by altering the coagulant solubility, increasing the water viscosity and retarding the kinetics of hydrolysis reactions and particle flocculation. Poly-aluminium coagulants are more effective in cold water than alum, as they are pre-hydrolysed. To achieve effective coagulation, proper mixing is also necessary to allow active coagulant species to be transferred onto turbid water particles (Gregory *et al*., 1997).

Proper mixing after addition of coagulants into raw water facilitates optimum removal of fine particles in the supernatant. This is because very fine particles become transformed into aggregates under good mixing condition (Kan *et al.*, 2002). It is commonly observed that particles are destabilised by small amounts of hydrolysing metal salts and that optimum destabilisation corresponds with the neutralisation of particle charge. Larger amounts of coagulants cause charge reversal so that the particles become positively charged and thus restabilisation occurs, which results in elevated turbidity levels. Thus, careful control of coagulant dosage is needed to give optimum destabilisation and this is determined to a large extent by the consistency of raw water quality (Gregory and Duan, 2001).

2.7 NATURAL MATERIALS AS COAGULANTS

The use of natural materials for treatment of drinking water in some parts of the world has been recorded throughout human history. However, these natural materials have not been recognized or duly supported due to lack of knowledge on their exact nature and the mechanism by which they function. As a consequence, the natural materials have been unable to compete effectively with the commonly used water chemicals (Ndabigengesere and Narasiah, 1998).

Recent research has focused on the development and use of natural coagulants which can be extracted or produced from plants, animals or microorganisms due to their presumed safety to humans and the environment. The application of natural materials of plant origin for clarifying turbid raw water from rivers is an ancient and domestic household practice in tropical developing countries where these natural materials act as primary coagulants due to their availability throughout the year. Different kinds of natural coagulants obtained from apricots (beach kernels), groundnut seed, nirmali seed, pumice seed, maize and the *Moringa oleifera* (MO) coagulant protein have been described in various reports.

Traditionally, treatment of turbid surface water sources is carried out at household level using local materials of plant or animal origin. For example, rural people in Sudan and Malawi, who depend on muddy water from rivers or intermittent streams, natural rain ponds and artificial rain-water catchments for domestic water supply, treat water fetched from such sources using *Moringa* seeds and other plant and soil materials (Jahn, 2001).

2.7.1 Types of Natural Coagulants

2.7.1.1 Materials of Soil Origin

It has been observed that mineral substances of soil origin are used as flocculation aid in modern water treatment. A dose of 10 mg/l of bentonite, for instance, together with 10 mg/l of aluminum sulphate, yield significantly better results than a higher dose of aluminum sulphate alone.

In rural households in developing countries various naturally occurring materials of soil origin are traditionally used as coagulants: e.g., fluvial clays from rivers and wadis (in Sudanese Arabic called "rauwaq", clarifier), clarifying rock material from desert regions, earth from termite hills. Their main constituents are quartz, montmorillonite, kaolinite, calcite and feldspar; their coagulating mechanisms differ greatly from those of metal salts. The processes and reactions which occur upon the addition of these various mineral coagulants to waters of different quality are not yet sufficiently known. This makes it difficult to specify optimal application procedures and conditions. Cases by case examinations are required. (Jahn, 2001)

Application of clay as a coagulant yields the following results:

- reduction of turbidity;
- no effect on pH value;
- an initial mineral taste, later on normal;
- no effect on bacteria count (more conclusive research is not available).

Potential health hazards:

- Clays contain traces of heavy metals (mostly chromium and manganese). High intakes of these metals may have toxic effects;

- viruses survive in the settled sludge.

2.7.1.2 Materials of plant origin

Such substances are widely used in developing countries to purify water. Usually the plants are not cultivated. Rather, according to passed on experience, certain substances are gathered, prepared and added to the water that is to be purified; seeds, leaves, pieces of bark, roots, fruit extracts and plant ashes.

Seed from the Moringa Olifera Tree

Moringa oleifera is a multipurpose tree belonging to the family of *Moringaceae*, a single family of shrubs with 13 known species. It is a tropical plant found throughout Asia, sub-Saharan Africa and Latin America. MO is widely recognized as a tree with almost every part of the plant utilized for beneficial purposes. Due to the diverse applications of MO, it is sometimes referred to as the miracle tree. The MO tree (Figure 2.4) is drought-tolerant and is generally used in the developing world as a vegetable, medicinal plant, nutrition supplement, cattle fodder, fertilizer and a source of oil. *Moringa oleifera* seeds are also very rich in iron and calcium and they contains 40% by weight of oil which can be used for cooking, lamp fuel and production of soap. It has been reported that the press cake remaining after oil extraction still contains active coagulants. The medicinal and therapeutic potential of MO is being utilized in the cure of different diseases and ailments. Among many other properties, seeds from MO contain a coagulant protein that can be used for water clarification. MO seed protein is known to be one of the most effective natural coagulants and the study on treatment of different kinds of waters has been growing recently (okoli, 2012).

Figure 2.4 *Moringa oleifera* tree with pods and seed kernels.

The active components of MO are water soluble cationic proteins with a molecular weight of 6.5 to 13 kDa and pI values around 10. Ndabigengesere et al. in his study, described the active coagulating agent of MO as a dimeric cationic protein having a molecular weight of 13 kDa and an isoelectric point between 10 and 11. The MO coagulant protein was identified as a heterogeneous mixture consisting of sixty amino acid residues. Moreover, extracts from MO seeds possess significant properties in the reduction of sludge volume and bacteria in contaminated waters without affecting the water pH, conductivity and alkalinity, thereby making the MO protein more attractive than aluminum salts in water treatment. Apart from being non-toxic, the MO protein is entirely biodegradable (okoli, 2012) .

The active component can be extracted from seeds by the use of water or salt solutions, usually NaCl. The use of MO seed protein in water treatment can be applied both at industrial scale where it can be used as a coagulant aid, or at the household level. Several reports suggest that the MO seed is more efficient when applied in high turbid waters; hence, its use in large scale water treatment during the spring season when water turbidity is at its highest level will benefit the water treatment plants that are forced to shut down due to lack of funding. The coagulation/flocculation mechanism of MO coagulant protein (MOCP) was described by Ndabigengesere *et al.*, as a mechanism involving adsorption and neutralization of charges, implying that the positively charged amino acids of this protein bind to the suspended or dissolved particles that are mainly negatively charged, and this leads to the formation of negatively and positively charged areas on the particle surface. Inter-particle neutralization of differently charged sectors and formation of flocs take place due to particle collision (Figure 2.5).

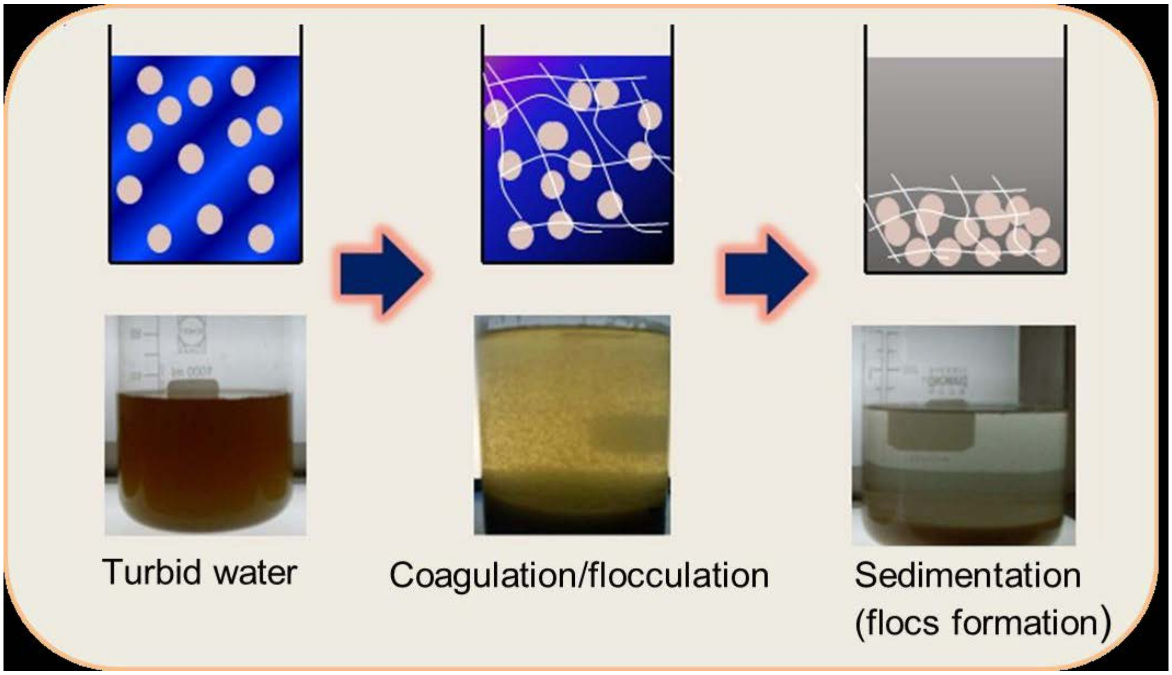


Figure 2.5 Mechanism of coagulation/flocculation with *Moringa oleifera* coagulation protein (MOCP) showing adsorption and neutralization of the colloidal charges with net-like structure.

Traditional water disinfection processes usually make use of chlorinated (chlorine and chloramine) chemical additives in eliminating the microbial contaminants. While their benefits are well established, concerns have also been raised about their safety issues. Conversely, MO seed extracts are capable of bacterial aggregation and removal. Their antimicrobial activity may lead to growth inhibition and killing of bacteria, including antibiotic-resistant human microorganisms. On the other hand, Broin *et al.* showed that a recombinant protein (MO2.1) of MOCP is capable of flocculating both Gram-Positive and Gram-negative bacterial cells. Microorganisms can be removed in this case by settling in the same way as the removal of colloids in well coagulated and flocculated water; alternatively, the protein may also act directly upon the microorganism, resulting in growth inhibition. The microbial growth inhibition might be mediated by the interaction of positively charged amino acids with the negatively charged surface of the microorganism's membrane. (okoli, 2012)

Apart from several advantages of the MO protein over chemical coagulants, the main drawback in using the crude extracts of MO seeds in water treatment is the release of organic matter and nutrients to the water. Previous studies show that crude seed extracts increase the organic, nitrate and phosphate contents in treated water, while the purified form (MOCP) does not. The presence of these organic loads is a source of odor, color and taste in water; moreover they also facilitate the growth of microorganisms upon storage, thus limiting the use of crude MO seed extract as a coagulant for water treatment in domestic and industrial levels. In order to overcome these limitations, the MO coagulant protein needs to be purified.

Consequently, the quest for low cost and simple purification procedures is critical for efficient maximization of natural coagulant in use. Previous reports imply that the MO purification process involves extensive methods that require several steps, which makes the purification system time consuming, complicated and expensive. Furthermore, it has become difficult to purify the protein on a large scale for water treatment applications. Recently, Habauka *et al*. employed a purification method that involves more than six steps, including dialysis. A single-step elution procedure was adopted by Ghebremichael *et al*. They developed a simple method for the purification of coagulant protein using ion-exchange matrix (IEX). While these methods are efficient, there are still some unresolved issues, such as the low binding capacity of the IEX matrix, the high cost of material as in the case of commercial beads, as well as long process times. These challenges can be a limiting factor which might potentially detract from the advantages of the aforementioned methods, bearing in mind the accessibility problem for people in the developing countries. (okoli, 2012)

Seeds from the Nirmali tree (strychnos potatorum)

S. potatorum (nirmali) is a moderate-sized tree found in Southern and central parts of India, Sri Lanka and Burma, used predominantly as a traditional medicinal extract. Sanskrit writings from India reported that the seeds were used to clarify turbid surface water over 4000 years ago which indicated that they were the first reported plant-based coagulant used for water treatment. Most studies concerning its use as coagulant seem to be limited within the Indian subcontinent. Nirmali seed extracts are anionic polyelectrolytes that destabilize particles in water by means of interparticle bridging. Previous studies have established that the seed extracts also contain lipids, carbohydrates and alkaloids containing the –COOH and free –OH surface groups which enhance the extracts' coagulation capability. A mixture of polysaccharide fraction extracted from S. potatorum seeds contained galactomannan and galactan capable of reducing up to 80% turbidity of kaolin solution. In all cases, the galactomannans are made up of a main chain of 1,4-linked d-mannopyranosyl residues bearing terminal d-galactopyranosyl units linked at the 0–6 position of some mannose residues. Although the specific coagulation mechanism associated with nirmali seed extracts has not been extensively investigated, one can surmise that the presence of copious amount of –OH groups along chains of galactomannan and galactan provides weakly but abundant adsorption sites that ultimately lead to the aforesaid coagulant interparticle bridging effect. Since both ionic (–COO−H+) and comparatively non-ionic (galactomannan) groups or substances are suggested to be present in the extract. (Vijayaraghavan,2011)

Maerua subcordata

Maerua subcordata is a wild shrub that is indigenous to many tropical countries and common in east Africa. It has coagulant properties and used in traditional water purification (Verdcourt and Trump, 1969). There are some communities that have been using the root for clarification of turbid water in many African countries. Jahn (1981, 1986) reported that the Pokomo communities in the Tana District of Kenya use M. subcordata branches and roots for drinking water clarification (Gedewon, 2009).

According to Edwards et al. (2000), M. subcordata is a low shrub, 1-2 m, and grows on rocky ground or on well-drained sandy soil; and also in grassland burned every few years and grazed by cattle. It grows in Ethiopia in Kefa, Gamo Gofa, Sidama as well as in Tanzania, Uganda, Kenya, Sudan and Somalia. The massive rootstock is pounded and mixed with muddy water to clear it for drinking and washing (Edwards et al., 2000). The concentration of protein was found to be an average of 289 mg/mL of M. subcordata juice (Mavura et al., 2008).

Fig. 2.6 Maerua subcordat (goulf) plant.

M. subcordata contains relatively large amounts of polysaccharides, 300 mg/L, mostly amylopectin which is a branched molecule. Special polysaccharides in the roots of M. subcordata are responsible for the flocculation of colloidal particles. These molecules form bridges between particles, increasing their mass as a consequence, thus causing precipitation (Mavura et al., 2008).

Tannin

Tannin is a general name given to large polyphenol compounds obtained from natural materials, for example, the organic extract from bark and wood of trees such as Acacia, Castanea, or Schinopsis. It is a polymer with molecular weights ranging from hundreds to tens of thousands and traditionally used as a tanning agent in the leather industry. There have been conflicting reports on the effect of tannin on human health and its portrayal in this negative light may have limited its application as natural coagulant for water treatment. The effectiveness of tannin as a natural coagulant for water treatment is influenced by the chemical structure of tannins that have been extracted from plant and degree of tannin modification. The presence of phenolic groups in tannin clearly indicates its anionic nature since it is a good hydrogen donor. Fig. 2.6 illustrates the schematic representation of basic tannin structure in aqueous solution and possible molecular interactions that induce coagulation. It is common knowledge that phenolic groups can easily deprotonate to form phenoxide which is stabilized via resonance. This deprotonation is attributed to delocalization of electrons within the aromatic ring which increases the electron density of the oxygen atom. This provides an indication that the more phenolic groups are available in a tannin structure, the more effective its coagulation capability. (Vijayaraghavan,2011)

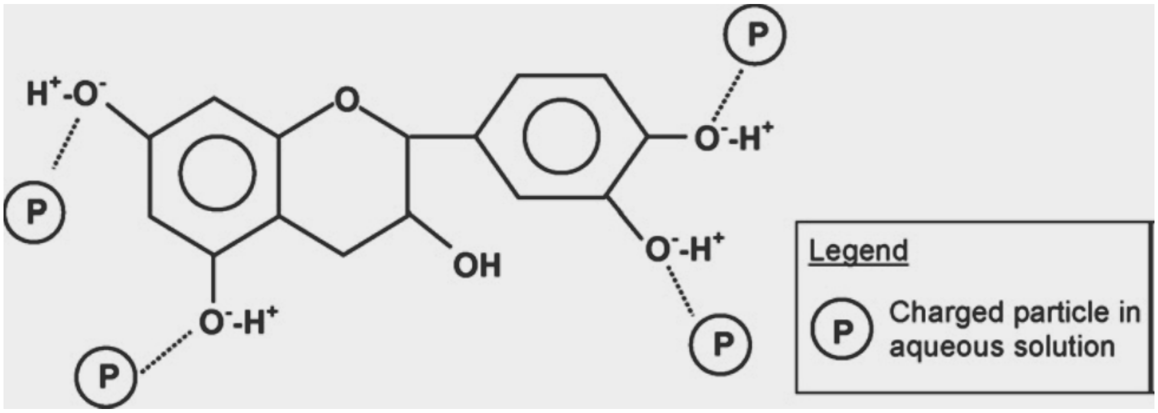


Figure 2.7 Schematic representation of basic tannin structure in aqueous solution and possible molecular interactions.

2.8 ORIGIN AND HISTORY OF CACTUS (Opuntia ficus-indica)

Opuntia ficus-indica is a species of cactus that has long been a domesticated crop plant important in agricultural economies throughout arid and semiarid parts of the world. Recent DNA analysis indicated OFI was domesticated from *Opuntia* species native to central Mexico. The Codex Mendoza, and other early sources, show *Opuntia* cladodes, as well as cochineal dye (which needs cultivated *Opuntia*), in Aztec tribute rolls. The plant spread to many parts of the Americas in pre-Columbian times, and since Columbus, have spread to many parts of the world, it was treasured by explorers for its properties and introduced to Europe, Asia, Australia and Africa where it rapidly adapted to various environments (Barbera, G. et all, 1992).

There are diverse views as to the ways of OFI introduction to Ethiopia. According to Kibra (1992), missionaries introduced cactus to Northern Ethiopia around 1847 and recently Habtu (2005) reported that Muslim pilgrimage from the Middle East introduced cactus to Southern Tigray of Northern Ethiopia in 1920. A survey indicated that about 30 520 ha (1.88% of the total area of the Tigray region) were covered with OFI 48.62% growing wild and 51.34% cultivated. Apart from Tigray, OFI is present predominantly also in other arid and semi-arid areas of Ethiopia. But, as can be seen in Debre Zeit and Bale, it also thrives in higher-rainfall highland areas.

According to Anaya-Pérez (2001) there are 377 species of the genus *Opuntia* of the Cactaceae family and are called *nopal*. The name "Opuntia" comes from an ancient Greek village in the region of Leocrid, Beocia: *Opus* or *Opuntia,* where Tournefort found a spiny plant which reminded him of America opuntia. The genus *Opuntia* includes 11 subgenera, namely: *Opuntia*, *Consolea*, *Austrocylindropuntia*, *Brasiliopuntia*, *Corynopuntia*, *Cylindropuntia*, *Grusonia*, *Marenopuntia*, *Nopalea*, *Stenopuntia* and *Tephrocactus* (Scheinvar, 1995; Reynolds & Arias, 2001). It is given different names in different countries; it is called kulekwal (Ethiopia), Nopal (mexico) and Prickly pear cactus (America).

The OFI is a succulent plant which grows up to 3-5 metres, many times in a dense and tangled structure. It´s recognized by its green thick long pads that look like sports rackets. They grow one linked to the next and can be considered as both leaves and stalks. The plant surface is covered by spines which help to conduct water, reduce water loss, and protect the succulent tissue from herbivores and other predators (Mondragon C., 1995).

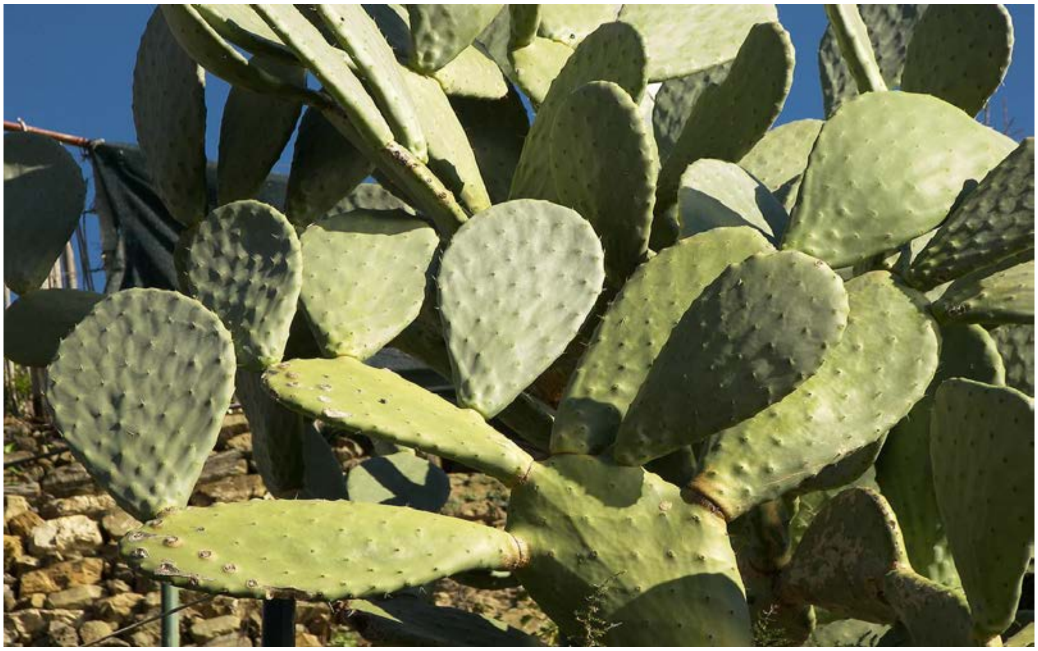


Figure 2.8 Cactus (Opuntia ficus-indica)

2.9 ECOLOGY AND CULTIVATION

OFI grows in a variety of soil types, but does best in well-drained sandy loam soils in dry, rocky flats or slopes. But some prefer mountain pinyon/juniper forests, while others require steep, rocky slopes in mountain foothills. OFI is extremely tolerant of high temperatures, but not air temperatures substantially below freezing (Nobel 1995).

OFI is characterized by a shallow, fleshy root system (side roots), with horizontal roots spreading (4 to 8 m) at a mean depth of about 15 to 30 cm to accumulate minerals from the upper part of the soil (Sudzuki Hills, 1995; Tegegne, 2001). It can form new roots within a few hours of wetting of a dry soil and disappear as soon as the soil dries out. This facilitates a quick response to light rainfall (Snyman, 2004). According to De Kock (1980) and Snyman (2006) the roots also have the ability to withdraw water from the soil at a stage when other crops fail to do so (Nobel 1995).

The OFI requires only that it be planted and left to grow on its own, without fertilizer or watering. The high efficiency of converting water in OFI biomass produces a high productivity value. For example a nopal fruit crop can generate production of 20 tonnes per hectare annually and produce up to 50 tonnes of dry material with the potential use as a natural coagulant (Moreno, 2009).

Figure 2.9 OFI leaves ready to grown

2.10 COMMON USES OF CACTUS (Opuntia ficus-indica)

2.10.1 NUTRITIONAL

Opuntia ficus-indica is widely used for its nutritional value. Opuntia is particularly attractive as a feed because its efficiency in converting water to dry matter and thus to digestible energy (Nobel 1995). It is used as a fruit crop and a vegetable crop for human consumption. The fruit of the *Opuntia* is commonly referred to as tunas, their Spanish name. Areas with significant tuna-growing cultivation include Mexico, Spain, Sicily and the coasts of Southern Italy, Greece, Tunisia, Morocco, Algeria, Egypt, Saudi Arabia, Yemen, Israel, Chile, Brazil, Turkey, as well as in Eritrea and Ethiopia where the fruit is called **beles** (Ge'ez: በለስ).Typically, the fruit is dried for use during the winter, but sometimes a sauce is made from boiled, unripe fruits. They are also used for their skins, (food coloring), their syrup (tuna honey), fermented and non fermented beverages, and in the dried form as tuna cheese. The seeds of the tuna have also been ground and used as a meal by some American Indians. The fruits of OFI contain water (92%), carbohydrates (4-6%), protein (1-2%), minerals (1%) and a moderate amount of vitamins, mainly A and C (Cantwell, 1991, and Neri, 1991, cited by Pimienta, 1993). They typically have a pH around 6.5 and are rich in calcium and phosphorous. The advantage of using *Opuntia* as a fruit crop is the ability to grow OFI in otherwise unfertile, rocky soil. Crop concentrations of 20,000 kg of fruit hectare have been produced, which equates to about 2,800 kg of sugar (Nobel 1995).

The use of OFI as a vegetable crop is less popular. Typically, only the young joints of the cactus (nopalitos) are used as a vegetable. Nopalitos are young green cladodes (stem-like organs) known as vegetables of less than one month of age, and are widely used in traditional Mexican cooking. They are typically cooked as a green vegetable or marinated as part of a salad. The OFI skin and thorns can be easily removed, leaving the edible insides of the OFI pad. *Opuntia* pads have been shown to be made up of 87% water, 1% protein, 0.1% fat, 1.3% ash, 1.1% crude fiber, and 5.4% carbohydrates (Nobel 1995).

In drought conditions, when grasses and other forage crops are no longer edible, the *Opuntia* cactus remains green and is used as an emergency feed crop for ranging livestock. The spines are burned off, soaked in water, or washed with soda to eliminate their harmful effects on the livestock. The spineless cactus pear has very high water content and when fed to animals little, if any, additional drinking water is needed for long periods. Sheep have lived for up to 8 months eating entirely *Opuntia* (Nobel 1995).

2.10.2 MEDICINAL USES

Moreover in Mexico and South America it is used to treat numerous maladies and researchers are interested in its medicinal use. Preparations of nopal are variously considered anti-diabetic, anti-inflammatory, analgesic, galactogogue, hypoglycemic, antiviral and anti-oxidant. Preparations have been used to regulate weight, blood sugar, increase fibber intake and facilitate childbirth and are used in the treatment of asthma, fatigue, liver injury following alcohol abuse, diarrhea, dysentery, dyspnoea, gastritis, colitis, gonorrhoea and syphilis, hypercholesterolemia, measles, nosebleeds, obesity, snakebite, sore throat, virginities, and inflammation of the eyes, among other disorders (Feugang, J. M, 2006, Duke, J. A. et all, 2002, Martínez, M, 1999).

FLOWERS - The use of OFI flower petals to treat urological problems is well-known in Sicily. Kidney colic treatment with OFI flowers was already mentioned by Pitrè (1896). They are also recognized the properties of the infusions of dried flowers to prevent prostate cancer.

Cladodes - are used in folk medicine for the treatment of gastric ulcer and for their healing activity as therapeutic agent.

2.10.3 Other uses

For soil and water conservation - OFI is easy to establish and helps rehabilitation of degraded lands. OFI is usually incorporated in re-afforestation programs for run-off and erosion control. OFI enriches top soil with organic matter and improves structure and stability of aggregates Hence permeability and water intake budget and balance is improved (Le Houerou 1996; Habtu 1996). Higher organic matter on soils with dense OFI in Mehoni (Habtu 2005). Significantly higher available phosphorus on soils with dense OFI plantations (Habtu 2005).

Bee forage - Cactus flowers in Jan to March Keeps bee colonies and prevents from absconding and thereby increases honey production in the area (Haile et al. 2002)

For Concrete - In Mexico, nopal juice is sometimes added to lime mortar to reduce cracking and water penetration. However, in investigating nopal mucilage’s role in the strength of the mortar, Cárdenas *et al*., found that, while it may decrease water penetration and cracking, it also reduces the mechanical strength of the lime mortar.

For Arsenic removal – OFI has great potential for the removal of heavy metals: specifically, arsenic. Young et al., found that, OFI mucilage can remove from 35 to 50% of total arsenic content from Ground water sources contaminated with arsenic (Satinder, 2008).

2.11 CACTUS AS A NATURAL COAGULANT

Historically, there is evidence to suggest the use of cactus mucilage for water clarification. Opuntia ssp. and cactus latiferi mucilage respectively were used by Chilean and Venezuelan indigenous peoples for centuries to remove pathogens and turbidity of surface water (Sutherland, J.P. et all 1990).

The ability of Cactus pear to retain water under unfavorable climatic conditions is due to the water-binding capacity of mucilage, which involves the consequent coagulation properties (Mindt L. et all, 1975). When it is mixed with water or other fluids, forms a sticky and slippery gel which has the capacity to catch the suspension particles and carry them to the bottom. Experiments suggest that the coagulation mechanism of OFI is not by charge neutralization like metallic salts, instead it occurs by adsorption and bridging mechanisms (Miller S. et all, 2008).

The mucilage of OFI is a thick, gummy substance and is what provides the cacti’s natural ability to store large amounts of water. When in water, the mucilage swells, producing unique surface-active properties seen in many natural gums, giving the mucilage a suspected ability to precipitate particles and ions from aqueous solutions. The mucilage is extracted from the pads of the cactus (Satinder, 2008).

Previous studies have established that mucilage in cactus Opuntia contains carbohydrates such as l-arabinose, d-galactose, l-rhamnose, d-xylose, and galacturonic acid. Galacturonic acid is possibly the active ingredient that affords the coagulation capability of Opuntia though it should be noted that it only accounts for only 50% of turbidity removal (miller, 2008). Nonetheless, this is still a significant quantum and therefore, this compound deserves further evaluation on its contribution to the overall coagulation capability of cactus. These studies point to the importance of galacturonic acid which possibly acts as one of the major active coagulating agents in plants and therefore, deserves further technical assessment. Though not extensively reported in open literatures, it is highly possible that galacturonic acid [a major constituent of pectin in plants] exists predominantly in polymeric form [polygalacturonic acid] that provides a ‘bridge’ for particles to adsorb on. Relevant dominant molecular interactions associated with adsorption and bridging in coagulation are shown in Figure 2.9. The polygalacturonic acid structure evidently indicates that it is anionic due to partial deprotonation of carboxylic functional group in aqueous solution. The existence of such functional groups along the chain of polygalacturonic acid implies that chemisorptions between charged particles and –COO− may occur although this requires further empirical substantiation. The presence of –OH groups along its polymeric chain also infers possible intra molecular interactions which may distort the relative linearity of the chain. (Vijayaraghavan,2011)

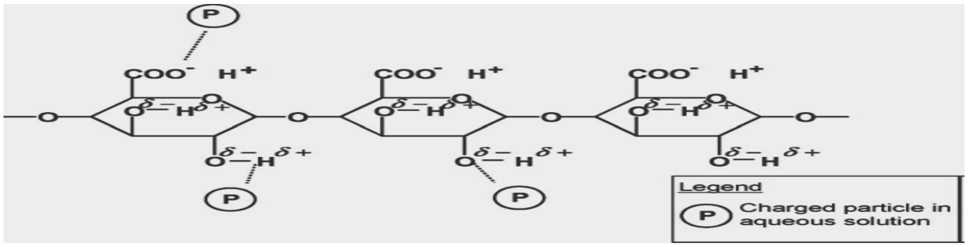


Figure 2.10 Schematic representation of polygalacturonic acid in aqueous solution and possible dominant molecular interactions associated with adsorption and bridging.

2.12 The DRINKING WATER TREATMENT IN ADDIS ABABA

The Metropolitan Area of Addis Ababa is at present supplied with three main surface water sources: the Legedadi-Dire reservoir, east of the city constructed in 1967 and 1998 respectively and the Geffersa reservoir west of the city constructed in 1943.

2.12.1 Legedadi Water Treatment Plant

The Legedadi reservoir total volume in 1998 was $4.38x10^6$ m^3 having a surface area of $4.8x10^6$ m^2; mean depth 9 m and maximum depth of 34m. Legedadi reservoir catchment area is 205 km^2. Steep slopes coupled with bare ground increase the amount of eroded materials, which deposit into the reservoir during the rainy seasons. Wastes moving into the reservoir include livestock dung and droppings, house refuses, feces and other wastes such as lubricating oil. Thus, the water quality is not always good especially the high content of suspended solids, taste and the odor. (TAHEL, 2000)

The Legedadi Water Treatment Plant (WTP) located about 30 kilometers east of Addis Ababa treats surface water supplied from the Legedadi and Dire water reservoirs. Treatment process consists of the following stages: prechlorination, coagulation, sludge blanket flocculation clarification, gravitational sand filtration and post-chlorinating. Treated water is impounded in a storage tank at the site before it is pumped to the capital. The treated water is delivered to the city by a 13 km long gravity pipeline. Sludge drawn off from the clarification basins and waste backwash water are disposed without any treatment to the Akaki river. (TAHEL, 2000)

The plant was designed for a maximum production rate of 150,000 m^3/day. It was constructed in two stages, stage 1 with production rate of 50,000 m3/day in 1970, and stage 2 with production rate of 100,000 m3/day in 1986. The Stage 2 plant was designed and constructed according to the experience gained during operation period of the Stage 1 plant. Degremont Company (France) designed both stages and they consist of Pulsator type Clarifiers and Aquazure sand filters. (TAHEL, 2000)

Coagulation designed to be based on Alum combined with polyelectrolyte. Because of low alkalinity of the raw water Lime was added to maintain pH value for optimal performance of Alum. In the first two decades of operation of the treatment plant high doses of Alum (50-60 mg/l) combined with polyelectrolyte was needed for appropriate operation of the treatment plant. During the last decade there was a tremendous deterioration of raw water quality in regard of turbidity and apparent color. As a result of that Alum was abandoned as coagulant and substituted with an organic cationic coagulant (Catfloc-Cl). (TAHEL, 2000) Nowadays the treatment plant uses PolyDADMAC as a coagulant and Polyacrylamide as a coagulant aid.

2.12.2 Geffersa Water Treatment Plant

Geffersa reservoir area, at maximum level, is $1.35x10^6$ m^2; total volume stored in 1998 is $6.23x10^6$ m^3; maximum depth 12m. The capacity of the reservoir was increased by the construction of an additional reservoir (Geffersa III) which has a surface area of $0.35x$ 10^6 m^2; a maximum depth of 18 m and a volume of $1.18x10^6$ m^3. Geffersa reservoir catchment area is 57 km^2. Generally, Geffersa catchment basin is different from Legedadi catchment basin because of the Geffersa III reservoir which functions as a “slit trap” upstream the main Geffersa reservoir. The soils in the Geffersa catchment area are more reddish and it is suggested (TAHAL, 1998) that they probably contain less montmorilonite type clay and more Kaolinite type clay with high content of iron oxides.

The Geffersa Water Treatment Plant (WTP) located west to Addis Ababa, treats surface water from the Geffersa water reservoir. Treatment process consists of the following stages: pre-chlorinating, coagulation, sludge blanket flocculation, clarification, gravitational sand filtration, post-chlorinating and final pH adjustment. The treated water is impounded in a storage tank at the site before it is pumped to the capital. Sludge from the clarification basins and waste backwash water drawn off and are disposed without any treatment to the River. (TAHEL, 2000)

The plant designed for a maximum production rate of 30,000 m3/day. It was constructed in two stages, stage 1 with production rate of 15,000 m3/day in 1954, and stage 2 with production rate of 15,000 m3/day in 1958. Degremont Company (France) designed both stages and they consist of Accelerator type clarifies and Aquazure sand filters.

The raw water from Geffersa main reservoir is gravitational feeded into the WTP. Relatively high turbidity and color, low alkalinity and hardness characterize the water. The yearly average turbidity is about 40 FTU with maximum values in the range 200-300 FTU in the rain season. The raw water suspended solids are coagulated and flocculated using Alum, Lime is added to maintain proper pH value. (TAHEL, 2000)

Table 2.3 consumption of Alum and Lime at Geffersa water treatment plant from 1997-2004 EC

Year	Alum (Kg)	Lime (kg)
1997	435,500	377,670
1998	427,550	389,260
1999	425,250	359,400
2000	489,250	283,750
2001	604,500	364,875
2002	823,750	545,050
2003	627,600	489,400
2004	610,750	335,500

3. MATERIALS AND METHODS

3.1 PREPARATION O F CACTUS POWDER

The *O. ficus-indica* Pads were collected from Addis Ababa in the suburb of saris and processed at Addis Ababa Water and Sewerage Authority Laboratory. Fresh OFI pads were collected prior to use in order to avoid ageing effects. Pads were rinsed thoroughly with tap water followed by deionized water. Dissections of fresh OFI pads were performed by hand: the spines were removed from the pad: skin was peeled from the pad; the outer pad was considered the outer layer of bright green tissue composed of chlorenchyma, and the inner pad was considered the inner layer of off-white tissue composed of parenchyma. The peeled OFI pads were sliced into small pieces to facilitate drying. The sliced pads were then dried in an oven for 32 hours at 55 ^{0}C. The dried pads were then grounded in a coffee grinder and sieved to obtain particles with less than 300 µm diameter. Stock solution was prepared by adding 5gram OFI powder to 1 liter of tap water. From 5kg of OFI Pads 100 gram of OFI powder can be obtained.

Figure 3.1 preparation of OFI powder

3.2 PREPARATION OF MORINGA OLIFERA POWDER

The dry *Moringa oleifera* seeds were collected from sodere. The seed wings and coat were removed manually, good quality seeds were then selected, and the kernel was grounded to a fine powder using a coffee grinder. The powder was weighed and dissolved in distilled water to make a 10 g/l stock solution.

3.3 COLLECTION OF SURFACE WATER SAMPLES

The sample waters for this study were collected from Legedadi and Geffersa water treatment plants. It was observed that the Legedadi raw water was more turbid and brown-yellowish in color. In contrast Geffersa raw water was less turbid and red-yellowish in color. Both raw waters were collected with plastic containers prior to immediate experimentation. Fresh water samples were collected prior to use in order to avoid ageing effects.

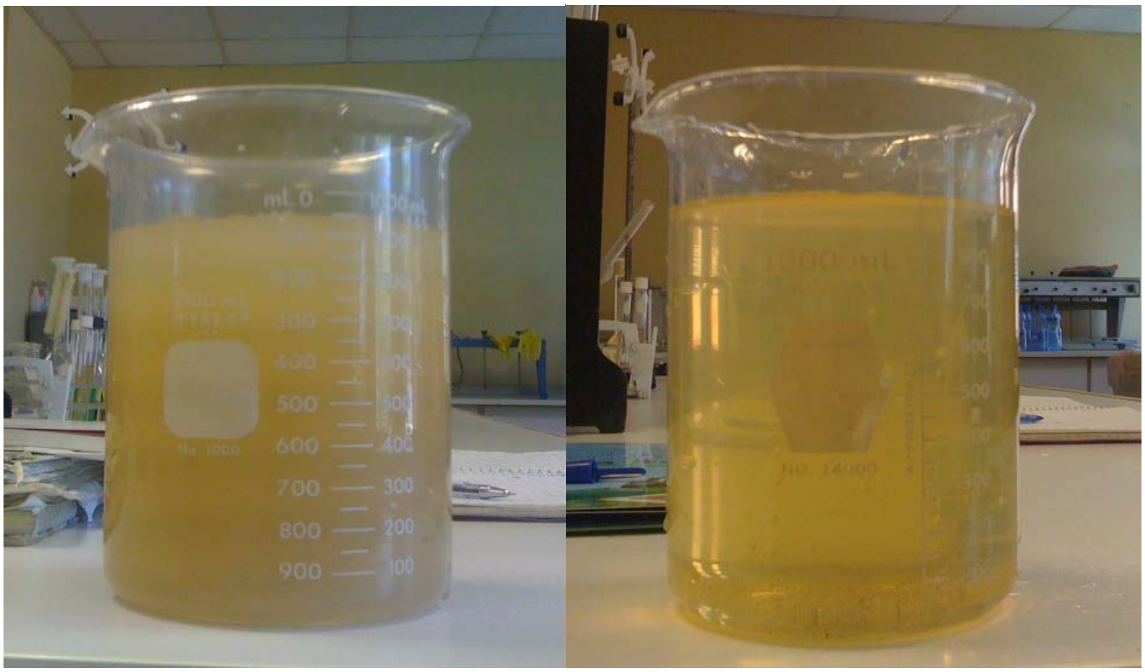


Figure 3.2 Legedadi and Geffersa raw waters respectively

3.4 PREPARATION OF SYNTHETIC WATER

Synthetic turbid water for the jar tests was prepared by diluting Legedadi raw water with tap water. The suspension was stirred for about 1 hour to achieve a uniform dispersion of colloids.

3.5 COAGULATION TEST

The jar test is a widely used method to evaluate coagulation- flocculation processes (Kawamura, 1991). The equipment used in this study was a Phipps & Bird jar test apparatus with 6 beakers (see figure 3.3). Each beaker was filled with 1 liter of raw water with identical turbidity level, and agitated at a rapid mixing speed of 120 rpm. A different volume of the selected coagulant was added to the 5 beakers. After 2 minutes the stirring rate was lowered to 40 rpm and this rate was kept for 20 minutes. This was followed by different sedimentation time for the different coagulants used. For OFI and PDADMAC 10 minute, for Alum 30 minute and for *M.oleifera* 1 hour sedimentation time was used. After the sedimentation phase, samples for turbidity measurement were collected from the supernatant using a standard pipette.

For each coagulant and turbidity level, three identical jar tests were carried out in order to obtain statistically reliable results. However, some of the parameters were only measured during one of these three jar tests and/or in the jar with the optimal dosage, due to restricted time and economic means. If the optimal dosage was not found in the jar test, a new jar test with new dosage was carried out until the optimum was found.

In each jar test experiment one of the six jars received no treatment, serving as a control for comparison of the turbidity reduction for all other jars. Coagulation activity was calculated using the equation:

$$Coagulation = \frac{(Residual\ turbidity\ blank - Residual\ turbidity\ sample)}{Residual\ turbidity\ blank} \times 100$$

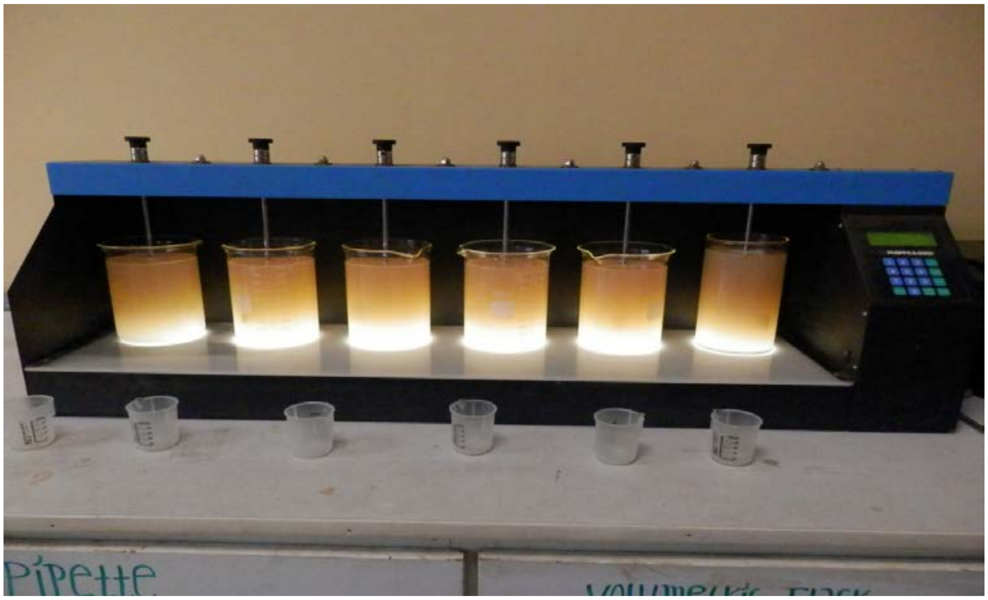


Figure 3.3 Phipps & Bird jar test apparatus

3.5 ANALYTICAL PROCEDURES

Turbidity measurements were conducted using a calibrated 2100AN turbidity meter from HACH. The turbidity meter cuvette was washed once with distilled water before recording the turbidity. In order to eliminate any differences in turbidity due to different sedimentation times, the supernatant from each beaker was taken at the same time.

PH and Temperature were measured with a Horiba PH meter made in Japan. The sensor was held in the sample until the pH-value was stabilized within a one decimal range. Between every reading, the sensor was cleaned with distilled water. Conductivity and TDS were measured with HACH CO150 conductivity meter. Sludge volume was measured using Imhoff cones.

Alkalinity was measured by means of Buret Titration Method. Three drops of Bromcresol Green-Methyl Red Indicator was added to 50 ml of sample. A 0.020 N Sulfuric Acid standard Solution was then added to the sample, using 725 Dosimat digital titration equipment from HACH. The added volume of acid was noted at the colour changes (from blue to light pink). The alkalinity was then calculated using the following equations:

$$\text{mg/L total alkalinity as CaCO3} = \text{mL Titrant} \times \text{multiplier used}$$

Table 3.1 Sample volume selection for expected concentration

Range (mg/L as CaCO3)	**Sample Volume (mL)**	**Sulfuric Acid**	**Multiplier**
0 – 500	50	20353	20
400- 1000	25	20353	40
100- 2500	10	20353	100
2000- 5000	5	20353	200

3.6 STATISTICAL ANALYSIS

All statistical analysis was carried out using both Microsoft Excel 2007 Edition and Statistical Package for Social Science (SPSS) 16.0.

4. RESULTS AND DISCUSSION

4.1 RAW WATER CHARACTERISTICS

The raw waters were analyzed for various water quality parameters, including pH, Turbidity, Conductivity, Total dissolved solid and Alkalinity. These parameters were measured just before each jar tests. These values were fairly stable throughout the experiment period, and are presented in table 4.1 below.

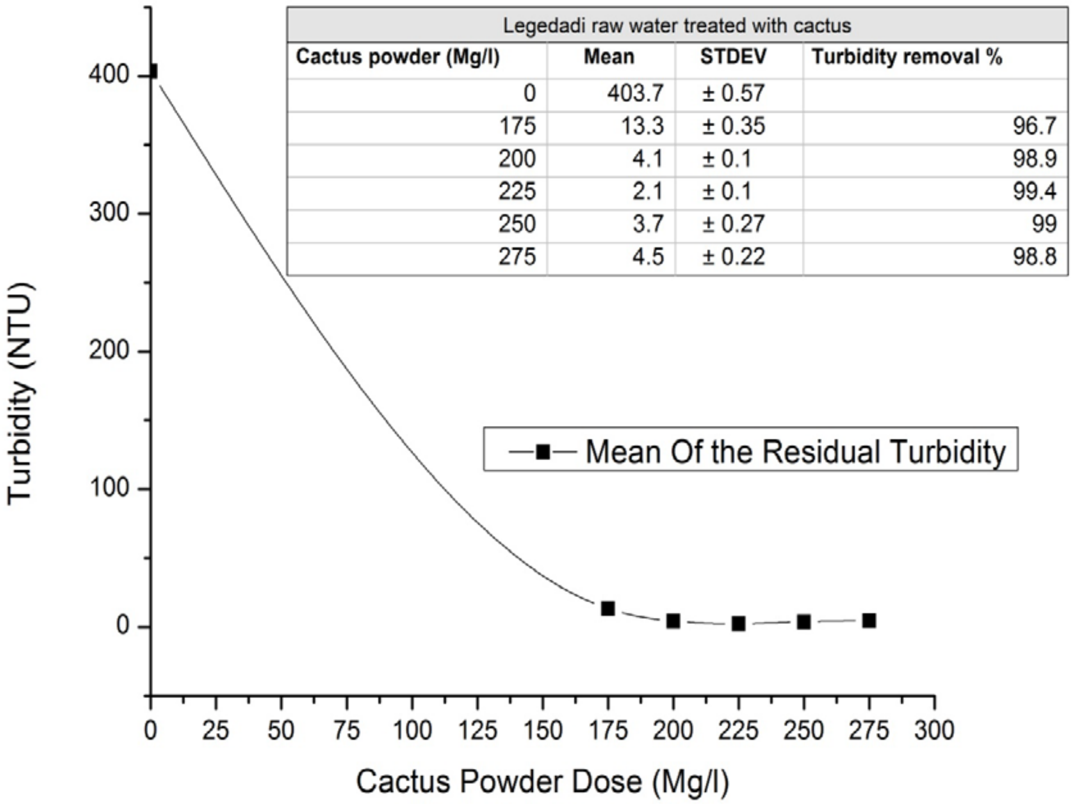
Table 4.1 Raw water quality of Legedadi and Geffersa raw waters

Water quality parameter	**Legedadi raw water**		**Geffersa raw water**	
	Average	**Range**	**Average**	**Range**
Turbidity (NTU)	397	390 – 404	58	55-61
pH	7.6		7.4	
Electrical conductivity (µs/cm)	130.1	128-132	73	71- 75
TDS (mg/l)	81.5	80-83	46	44 – 48
Alkalinity (mg/l as $CaCO_3$)	37.6		24	

The Legedadi raw water was considered as high turbidity water because the turbidity is higher than 250 NTU. In contrast the Geffersa raw water is considered as low turbidity Water because the turbidity is in the range between 0-125 NTU (miller, 2008). Both Legedadi and Geffersa raw waters are only slightly alkaline. The Legedadi raw water EC and TDS was higher than the Geffersa raw water. Both raw waters were considered as low alkalinity because their alkalinity is in the range between 10 – 50 mg/l as $CaCO_3$.

4.2 EFFECT OF CACTUS DOSAGE ON TURBIDITY REMOVAL

The turbidity removal efficiency of OFI powder was tested on Legedadi and Geffersa raw waters. As it can be seen on Figure 4.1, For Legedadi raw water the turbidity removal efficiency reached 99.4 percent. The dosage that showed the best turbidity removal efficiency was 225 mg/l and a residual turbidity of 2.1 NTU was recorded 10 minute of settling.



Legedadi raw water treated with cactus

Cactus powder (Mg/l)	Mean	STDEV	Turbidity removal %
0	403.7	± 0.57	
175	13.3	± 0.35	96.7
200	4.1	± 0.1	98.9
225	2.1	± 0.1	99.4
250	3.7	± 0.27	99
275	4.5	± 0.22	98.8

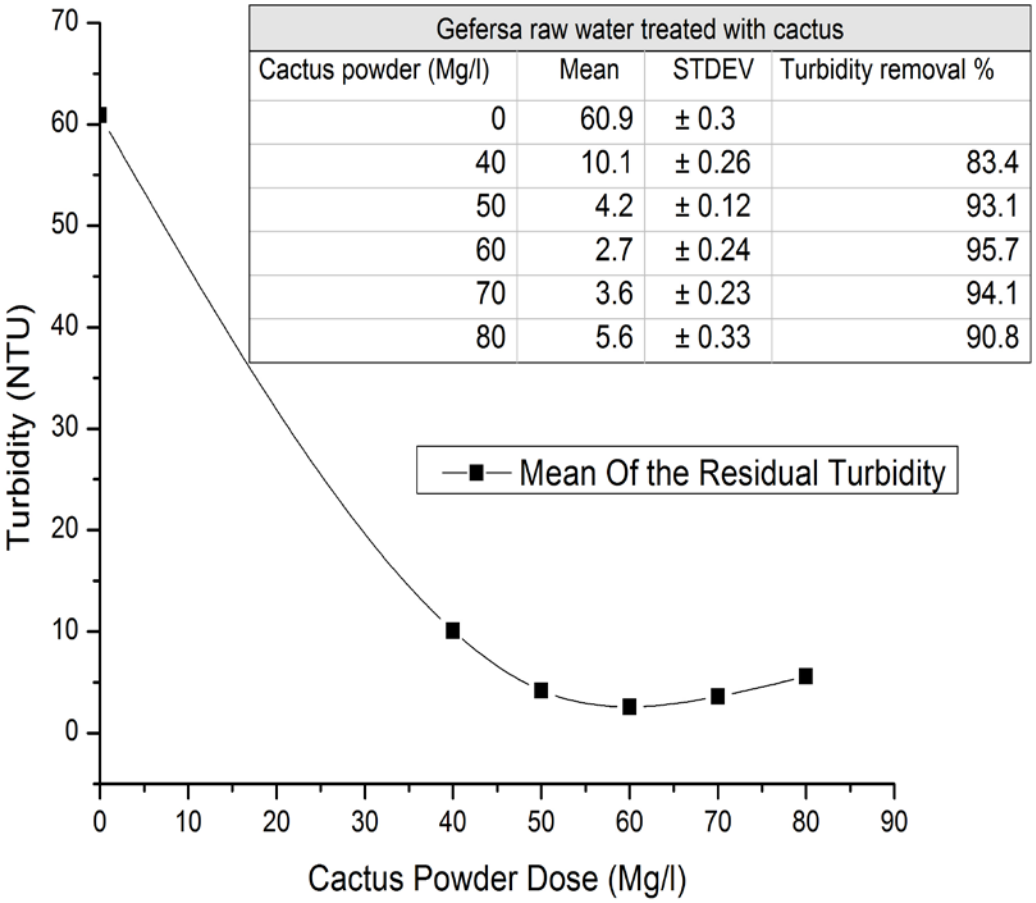
Figure 4.1 Removal of Turbidity using various dose of OFI (for Legedadi water)

For the raw water treated with the optimum dosage different water quality parameters were measured. As it can be seen on Table 4.2, the PH decreased slightly from 7.6 to 7.46, both the EC and TDS increased significantly with increase in dosage. The increase in EC and TDS may be attributed to the presence of large amount of the divalent calcium and appreciable amount of the monovalent potassium ions the OFI's mucilage is known to have (Naod, 2012). The alkalinity increased from 37.6 to 40.5 mg/l as $CaCO_3$.

Table 4.2 Measured Water quality Parameters For the optimum dosage (225 Mg/l)

	Mean	**STDEV**
PH	7.46	± 0.03
EC	161.7	± 0.7
TDS	102.1	± 0.3
Alkalinity	40.4	± 0.5
SVI	29.3	± 0.58

For Geffersa raw water also the turbidity removal efficiency of OFI reached 95.7 percent. The dosage that showed the best turbidity removal efficiency was 60 mg/l and a residual turbidity of 2.6 NTU was recorded after 10 minute of settling. This was compared with the finding of a study conducted by Zhang et al (2006) where the optimum dosage of cactus opuntia used for turbidity removal of river water (50 NTU) was 50 mg/L. In that study, the highest removal efficiency reached 92% which was comparatively similar to the highest removal efficiency obtained for treated reservoir water (95.7%) in this study.



Gefersa raw water treated with cactus

Cactus powder (Mg/l)	Mean	STDEV	Turbidity removal %
0	60.9	± 0.3	
40	10.1	± 0.26	83.4
50	4.2	± 0.12	93.1
60	2.7	± 0.24	95.7
70	3.6	± 0.23	94.1
80	5.6	± 0.33	90.8

Figure 4.2 Removal of Turbidity using various dose of OFI (for Geffersa water)

For the optimum dosage different water quality parameters were measured. As the Legedadi raw water the PH decreased slightly. The EC and TDS increased significantly with increase in dosage. The alkalinity increased slightly from 24 to 26.9 mg/l as $CaCO_3$.

Table 4.3 Measured Water Quality Parameters For the optimum dosage (60 Mg/l)

	Mean	**STDEV**
PH	7.34	± 0.04
EC	89.8	± 0.55
TDS	56.5	± 0.35
Alkalinity	26.8	± 0.34
SVI	14.6	± 0.58

When OFI powder stock solution is added into the water sample, it disperses and after 40 seconds threadlike strands are formed. During the slow mix stage these threadlike strands grow in size decrease in turbidity in the sample water was observed. During the sedimentation time the flocs settle quickly within 10 minutes.

This result support the hypothesis by miller 2008 which states that the predominant coagulation mechanism for *Opuntia* spp. is adsorption and bridging, whereby clay particles do not directly contact one another but are bound to a polymer-like material from *Opuntia* spp. Adsorption may occur through hydrogen bonding or dipole interactions. It is likely that natural electrolytes from within the *Opuntia* spp. pad, particularly the divalent cations, which are known to be important for coagulation with anionic polymers, facilitate adsorption.

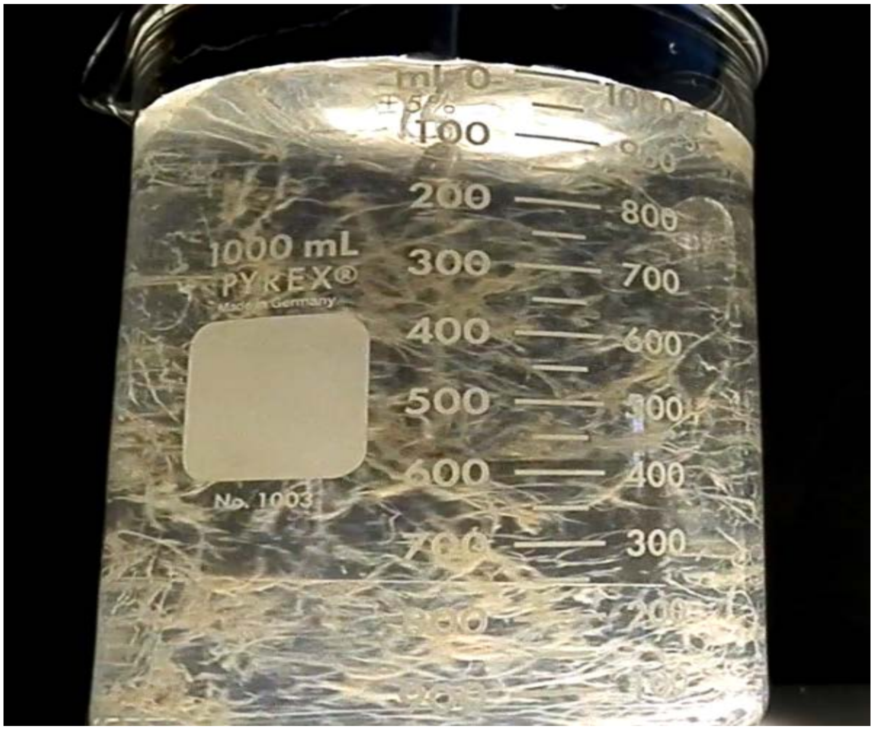


Figure 4.3 Threadlike strands formed during the addition of OFI

4.3 COMPARISION OF CACTUS WITH PolyDADMAC, Alum and Moringa Olifera

The coagulation activity of OFI powder was compared with PolyDADMAC, Alum and *M. oleifer*. For Legedadi raw water OFI powder efficiency was compared with PolyDADMAC which is currently being used at Legedadi water treatment plant and with the other natural coagulant *M. oleifera.*

As it can be seen on Table 4.4, the coagulation efficiency of PolyDADMAC was 99.5 %. The optimal dosage was 10 mg/l and a residual turbidity of 2 NTU was recorded after 10 minute of settling. It was observed that coagulation and flocculation using PolyDADMAC as a coagulant and Polyacrylamide as a coagulant aid did not affect the PH, EC, TDS or the Alkalinity.

Table 4.4 Mean value and standard deviation of residual turbidity and Percentage Turbidity removal for Legedadi raw water

PolyDADMAC Dose (Mg/l)	**Polyacrylamide Dose (Mg/l)**	**Mean (NTU)**	**STDEV**	**Turbidity removal %**
0	0	403.1	± 0.17	
7	0.5	7.6	± 0.13	98.1
8	0.5	4.8	± 0.18	98.8
9	0.5	3.5	± 0.19	99.1
10	0.5	2	± 0.11	99.5
11	0.5	3.1	± 0.18	99.2

When compared with PolyDADMAC, OFI showed the same turbidity removal efficiency although the amount of OFI consumed was much higher. The high consumption of OFI in Legedadi raw water may be due to high organic matter content of the water. Recognizing that coagulant dose can be controlled by levels of NOM, rather than turbidity (Edzwald, J. K. 1993). The amount of sludge produced by OFI was also higher than PolyDADMAC. Another drawback observed in the use of OFI for Legedadi raw water is the sludge was more slippery and it stuck on the Paddle.

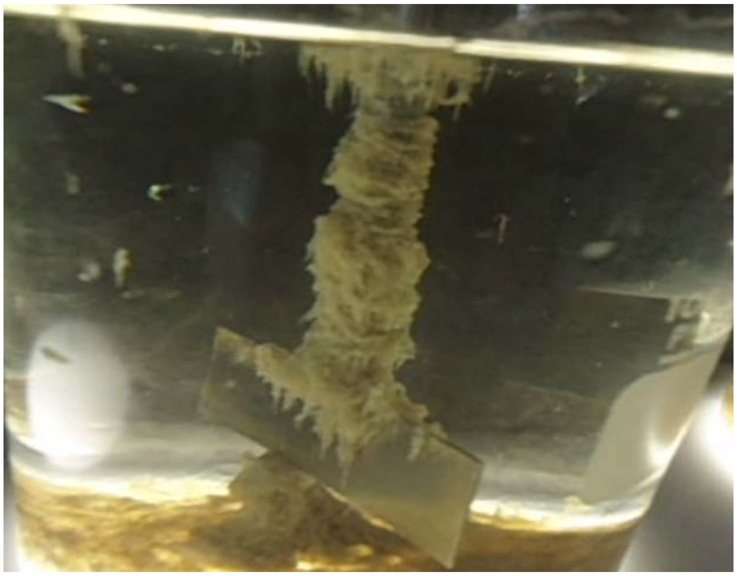


Figure 4.4 OFI sludge stuck on the paddle

M. oleifera also showed good turbidity removal efficiency for Legedadi raw water. As it can be seen on Table 4.5, the coagulation efficiency of *M. oleifera* reached 98.9 %. The optimal dosage was 100 mg/l and a residual turbidity of 4.2 NTU was recorded after 1 hour of settling.

Table 4.5 Mean value and standard deviation of residual turbidity and Percentage Turbidity removal for Legedadi raw water

Moringa Dose (Mg/l)	**Mean of Residual Turbidity (NTU)**	**STDEV**	**Turbidity removal %**
0	395.3	± 0.58	
80	6.4	± 0.45	98.4
100	4.2	± 0.45	98.9
120	5.9	± 0.27	98.5
140	7.7	± 0.48	98
160	14.1	± 0.31	96.4

M. oleifera did not significantly affect the pH-value which remained almost constant at 7.5 for all dosages tested. This is line with previous study which has shown that the use of *M. oleifera* does not cause alteration in pH (Ndabigengesere and Narasiah, 1998). The EC and TDS increased significantly with increase in dosage. The alkalinity only showed a slight decrease.

Table 4.6 Measured Water Quality Parameters For the optimum dosage (100 Mg/l)

	Mean	**STDEV**
PH	7.5	± 0.01
EC	143	± 0.55
TDS	90.1	± 0.35
Alkalinity	35.9	± 0.23
SVI	20	± 0

For Geffersa raw water, OFI powder efficiency was compared with Alum which is currently being used at Geffersa water treatment plant and *M. oleifera.* As it can be seen from Table 4.7, the coagulation efficiency of Alum reached 96.1 %. The optimal dosage was 30 mg/l and a residual turbidity of 2.4 NTU was recorded after 30 minute of settling.

Table 4.7 Mean value and standard deviation of residual turbidity and Percentage Turbidity removal for Geffersa raw water

Alum Dose (Mg/l)	**Lime Dose (Mg/l)**	**Mean (NTU)**	**STDEV**	**Turbidity removal %**
0	0	61	± 0	
20	6.7	6.8	± 0.13	88.8
25	8.3	5.2	± 0.06	91.4
30	10	2.7	± 0.15	95.5
35	11.7	2.3	± 0.05	96.1
40	13.3	4.3	± 0.12	93.1

Coagulation and flocculation using alum with lime significantly affects the PH. The PH decreased from 7.4 to 6.7 even if lime was used. The EC and TDS show only a slight increase with increase in dosage. The alkalinity decreased from 24 to 20 mg/l as $CaCO_3$.

Table 4.8 Measured Water Quality Parameters For the optimum dosage (30 Mg/l)

	Mean	**STDEV**
PH	6.7	± 0.05
EC	82.3	± 0.5
TDS	51.9	± 0.3
Alkalinity	20.1	± 0.1
SVI	7	± 0

When compared with Alum, cactus showed almost the same turbidity removal efficiency on Geffersa raw water. The flocs formed by Alum were much smaller in size than OFI they were also relatively spherical in contrast the flocs formed by OFI were long, thin and threadlike. Alum significantly decreased the PH and Alkalinity of the treated water even if lime was used. The sludge produced by OFI was higher than Alum.

M. oleifera did not show good turbidity removal efficiency for Geffersa raw water. The turbidity removal efficiency only reached 85%. This is line with previous study which has shown that the use of *M. oleifera* is less effective on low turbidity water (< 100 NTU) (Abaliwano, J. K., Ghebremichael, K. A., Amy, G.L., 2008).

Table 4.9 Mean value and standard deviation of residual turbidity and Percentage Turbidity removal for Geffersa raw water

Moringa Dose (Mg/l)	Mean of residual turbidity (NTU)	STDEV	Turbidity removal %
0	55.4	± 0.12	
20	10.6	± 0.4	80.8
35	8.3	± 0.25	85
30	15.8	± 0.32	71.4
35	17.6	± 0.36	68.3
40	21.8	± 0.55	60.8

When compared with *M. oleifera*, OFI turbidity removal efficiency was higher on both raw waters. The flocs formed by *M. oleifera* were much smaller than OFI. For both coagulants, the optimal dose for a given water increase as the initial turbidity increase. The advantage of using OFI over Moringa is that the flocs produced by Moringa are very small and it takes a long time for the flocs to settle.

4.4 CACTUS AS A COAGULANT AID

The effectiveness of OFI as a coagulant aid was also tested on Geffersa and Legedadi raw waters. On Geffersa raw water a combination of alum with OFI and *M. oleifera* with OFI was tested. On Legedadi raw water only a combination of *M. oleifera* with OFI was tested.

The use of alum as a coagulant and OFI as a coagulant aid did not show significant turbidity removal efficiency. As it can be seen on table 4.10, the turbidity removal efficiency only reached 82.9 %. This may be due to the decrease in the PH of the water during the addition of Alum.

Table 4.10 Mean value and standard deviation of residual turbidity and Percentage Turbidity removal for Geffersa raw water

Alum Dose (mg/l)	OFI Dose (Mg/l)	Mean (NTU)	STDEV	Turbidity removal %
0	0	56	± 0	
2	15	11.7	± 0.29	79.1
4	15	11.4	± 0.3	79.6
6	15	9.6	± 0.42	82.9
8	15	10.6	± 0.15	81

10	15	13.8	± 0.42	75.7

The use of *M. oleifera* as coagulant and OFI as a coagulant aid shows a promising result on both Legedadi and Geffersa raw waters. The turbidity removal efficiency reached 99.3 % and 96 % respectively on Legedadi and Geffersa waters. For Legedadi raw water, the optimal dosage was 30 mg/l Moringa Olifera and 40 mg/l OFI. A residual turbidity of 2.7 NTU was recorded after 10 minutes of settling. For Geffersa raw water, the optimal dosage was 15 mg/l Moringa Olifera and 10 mg/l OFI. A residual turbidity of 2.2 NTU was recorded after 10 minutes of settling.

Table 4.11 Mean value and standard deviation of residual turbidity and Percentage Turbidity removal for Legedadi raw water

Moringa Dose (Mg/l)	**OFI Dose (Mg/l)**	**Mean**	**STDEV**	**Turbidity removal %**
0	0	395.3	± 0.58	
20	40	4.8	± 0.26	98.8
30	40	2.7	± 0.21	99.3
40	40	3.2	± 0.21	99.2
50	40	6.1	± 0.18	98.4
60	40	6.7	± 0.37	98.3

Table 4.12 Mean value and standard deviation of residual turbidity and Percentage Turbidity removal for Geffersa raw water

Moringa Dose (Mg/l)	**OFI Dose (Mg/l)**	**Mean (NTU)**	**STDEV**	**Turbidity removal %**
0	0	55	± 0	
5	10	5.6	± 0.30	89.7
10	10	2.8	± 0.15	94.9
15	10	2.2	± 0.13	96
20	10	3.5	± 0.24	93.5
25	10	4.3	± 0.27	92.6

Coagulation using Moringa Olifera as a coagulant and OFI as a coagulant aid did not significantly affect the PH for both water samples. The EC and TDS increased with increase in dosage. The alkalinity didn't show any change.

Table 4.13 Measured Water Quality Parameters For the optimum dosages (30 mg/l *M. oleifera* and 40 mg/l OFI)

	Mean	**STDEV**
PH	7.5	± 0.01
EC	145.3	± 0.68
TDS	91.6	± 0.43
Alkalinity	37	± 0.4
SVI	15	± 0

Table 4.14 Measured Water Quality Parameters For the optimum dosages (15 mg/l *M. oleifera* and 10 mg/l OFI)

	Mean	**STDEV**
PH	7.3	± 0.02
EC	81	± 0.4
TDS	51	± 0.25
Alkalinity	24	± 0
SVI	5	± 0

During the test using Moringa olifera as a coagulant and OFI as a coagulant aid it was observed that clear water was visible even during the rapid mixing time and the flocs already start to settle during the slow mixing stage. Because of this the test was done lowering the slow mixing time from 20 to 10 minutes and the same turbidity removal efficiency was observed.

The use of *M.oleifera* as a coagulant and OFI as a coagulant aid was found to be more advantageous than using OFI or *M.oleifera* as a coagulant alone.

- Fewer amounts OFI can be used which can decrease the organic matter loading.
- It solves the problem of *M.oleifera* on low turbid water and decrease the settling time from 1 hour to only 10 minutes.
- Less amount of sludge is produced.
- The coagulation time can be decreased by 10 minute.

The most important contribution that this study provides is that to date, the work produced by other researchers has concentrated on only one kind natural coagulant or combining a natural coagulant with other chemical coagulant. This research, on the other hand, dealt with the combination of two natural coagulants.

4.5 FACTORS AFFECTING COAGULATION EFECTIVENESS OF CACTUS

Several parameters were checked for their effect on OFI coagulant performance. These included; rapid mixing time, slow mix time, sedimentation time, pH, temperature and initial turbidity. The effectiveness of OFI coagulant did not show significant changes with change in rapid mix intensity, time and sedimentation time. However an improvement was noted when slow mix time was increased from 10 minutes to 20 minutes.

Another factor that affects turbidity removal efficiency is the initial turbidity level different scholars have shown that *M. oleifera* is less effective for low turbid water. OFI performance was checked on synthetic waters with initial turbidity 10 NTU and 30 NTU. As it can be seen on figure 4.5, a residual turbidity of 1.4 and 1.5 NTU was recorded for 10 and 30 NTU synthetic waters respectively. OFI turbidity removal efficiency did not decreased with decrease in initial turbidity.

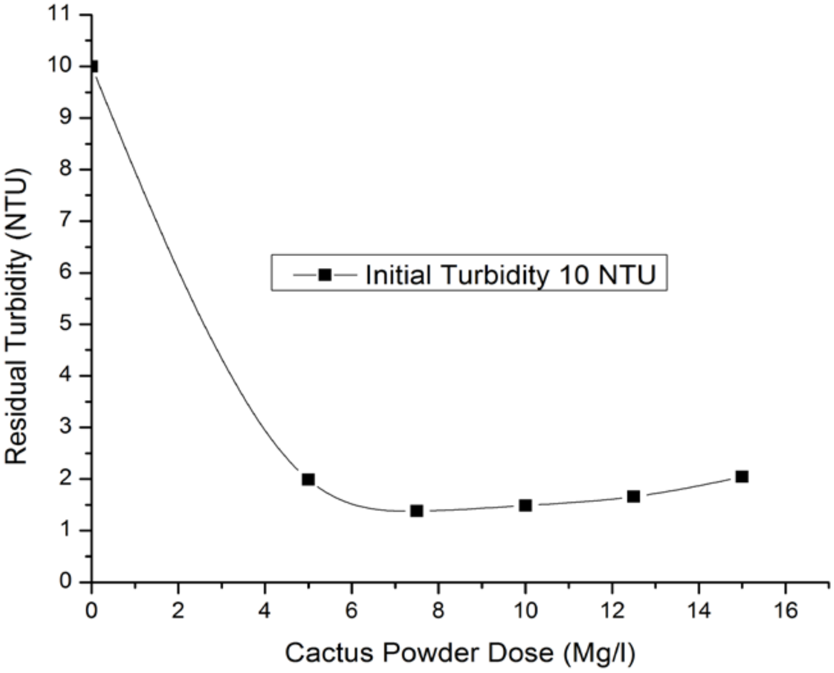


Figure 4.5 OFI coagulant performance for an initial turbidity of 10 NTU

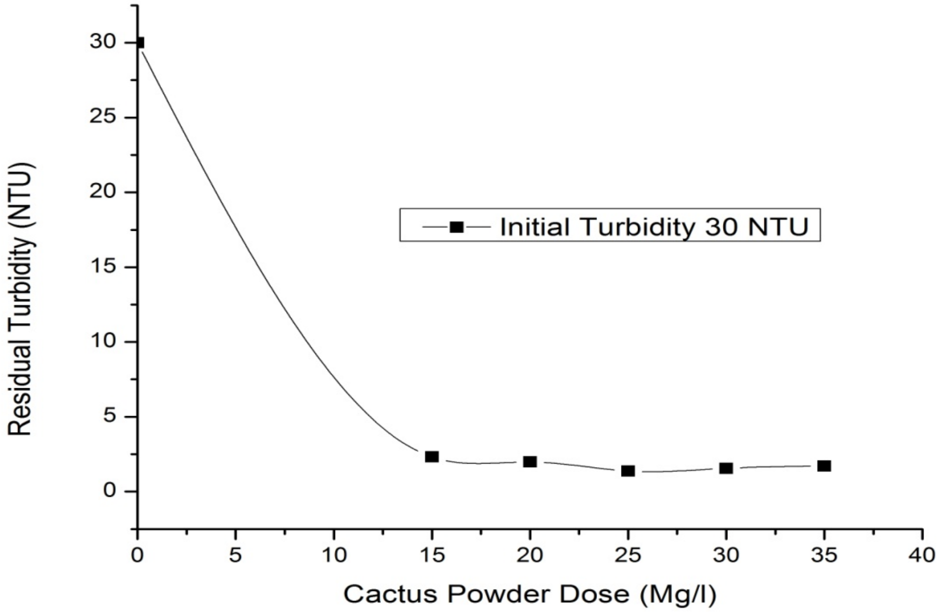


Figure 4.6 OFI coagulant Performance for initial turbidity of 30 NTU

PH is an important factor that affects the turbidity removal efficiency of different coagulants. The effectiveness of OFI dosage at different PH values was compared. As it can be seen on figure 4.5, the optimum PH was at about at PH 10 and the worst effect appeared at about PH 4. This was compared with the finding of a study conducted by Zhang et al. (2006) in his study OFI was most effective at pH 10 and is least effective at pH 6.

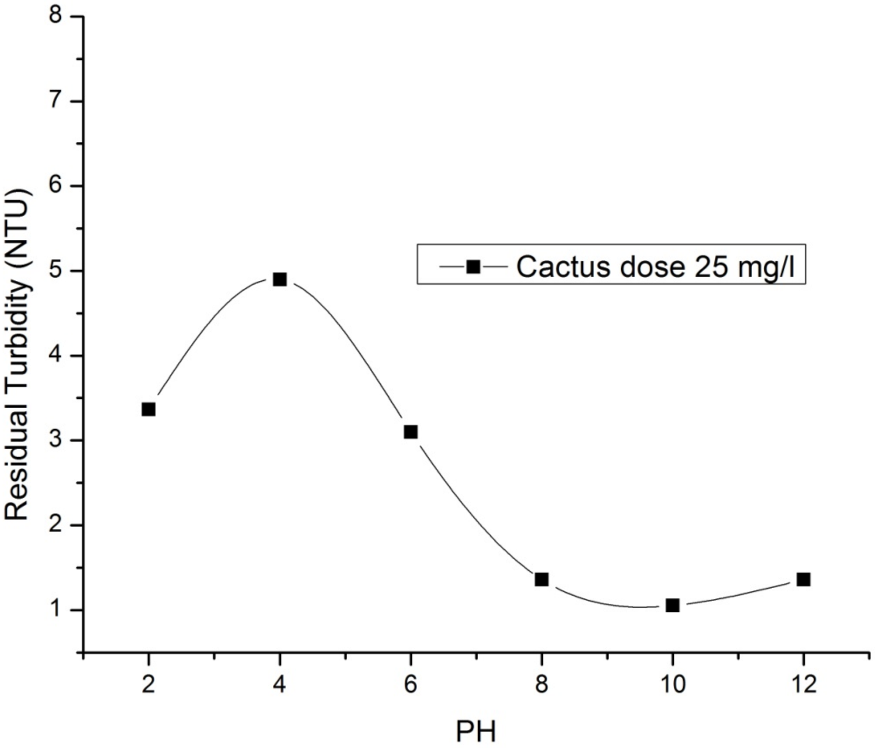


Figure 4.7 OFI coagulant performances on different PH values

Temperature is also an important factor that affects coagulation efficiency. The relationship between OFI dosage and the turbidity removal efficiency with different temperatures was compared. As it can be seen figure 4.8, the coagulation activity at 10^0c was a little worse than at 20^0c and turbidity removal efficiency increased with increase in temperature.

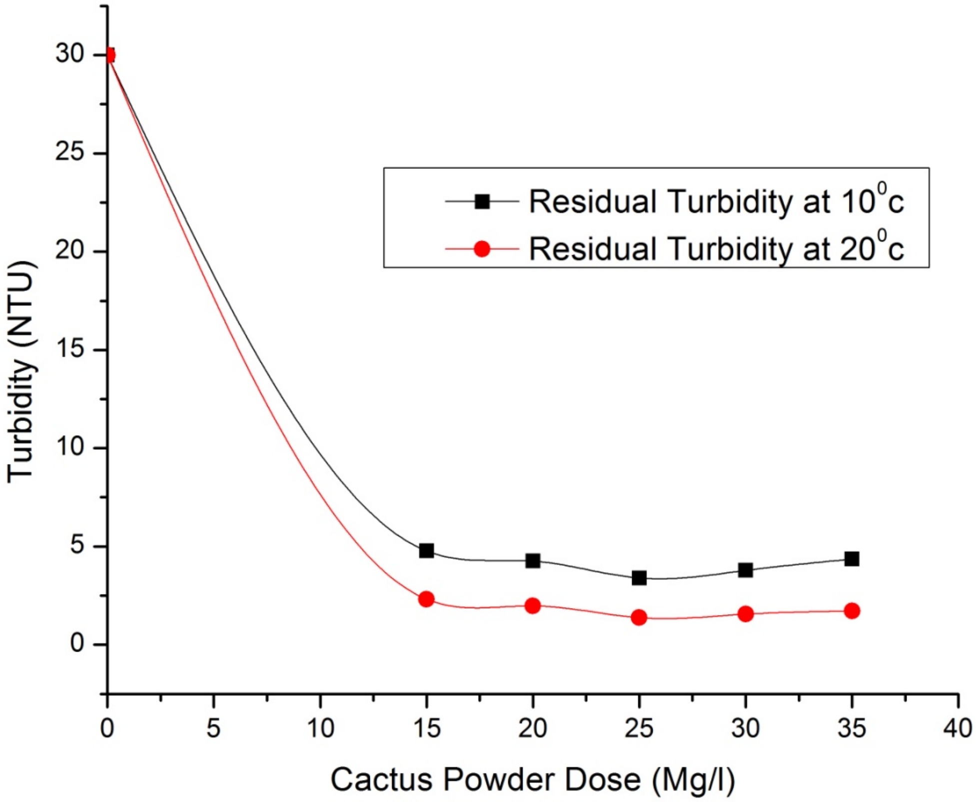


Figure 4.8 OFI coagulant of different dosage to treat synthetic water with initial turbidity of 30 NTU and under different temperature

5. CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

The overall aim of this research was to test the efficiency of OFI mucilage in removing turbidity from surface water source. Natural coagulant from OFI pad was prepared by drying the pad in an oven and grounding the dried pad by a coffee grinder. The OFI powder efficiency as a coagulant was tested on surface water samples obtained from Legedadi and Geffersa water treatment plants as well as its efficiency was compared with other chemical coagulants (PolyDADMAC and Alum). Also the use OFI as a coagulant aid for Alum and Moringa olifera and factors affecting coagulation effectiveness of OFI were tested.

As a primary coagulant the OFI powder removed 99.4 and 95.7 % turbidity from Legedadi and Geffersa raw waters respectively within 10 minutes of settling. OFI powder did not significantly affect the PH in contrast it significantly increased the EC and TDS. From the above result it can be concluded that OFI has very good turbidity removal efficiency when used as a coagulant alone.

When compared with other chemical coagulants, the turbidity removal efficiency of OFI powder was the same as PolyDADMAC and Alum. In contrast, when compared with the other natural coagulant Moringa Olifera, OFI powder gave better result in terms of turbidity removal.

As a coagulant aid OFI powder did not perform well with Alum but with Moringa Olifera promising results were obtained. The use of Moringa Olifera as a coagulant and OFI as a coagulant aid was found to be more advantageous than using OFI and Moringa Olifrea as a primary coagulant alone.

Different factors were checked for their effect on the turbidity removal efficiency of OFI powder. Initial turbidity level did not affect the turbidity removal efficiency of OFI. At different PH values OFI showed different turbidity removal efficiency the Optimum result was found at PH 10 and the worst at PH 4. Decrease in temperature from 20^0c to 10^0c slightly affected the turbidity removal efficiency of OFI.

The low cost of the raw material and the availability of OFI throughout the year are the added advantages and OFI might be a good complement to Moringa and chemicals in drinking water treatment. The technology of using natural coagulants for treatment of water is most appropriate in developing countries, especially in rural areas, where they cannot afford the high cost of conventional coagulants.

5.2 RECOMMENDATIONS

1. There is a need for public education on uses of Cactus (OFI) in water clarification in Ethiopia.

2. Government and private organizations should invest more in OFI and Moringa Olifera cultivation since they have the potential of reducing cost of water treatment and can help improve water quality for rural dwellers.

3. Most researches done up to date only concentrate only on one kind of natural coagulant this research has shown that by combining natural coagulant good result can be obtained. So there is a need to do more research by combing natural coagulant together.

4. Further research is suggested on the following:

- It is necessary to examine the influence of NOM on turbidity removal by OFI.
- Antimicrobial properties of OFI need to be investigated.
- The use of natural coagulants may increase the organic load in waters resulting in the possibility for undesired and increased microbial activity. Thus, the active component of OFI which is responsible for its coagulation behavior must be clearly known.
- Toxicity studies should be conducted to insure its safe use.
- There is a Need for plot scale studies on the plant to determine its applicability in community water supplies and at house-hold level.
- The use of OFI as a coagulant in municipal wastewater and industrial wastewater treatment should be conducted.

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Appendices

Appendix A: OFI as a primary coagulant

Coagulant: OFI
Raw water – From Legedadi water treatment plant

11-10-2012	**Treated Water**					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume (ml)	35	40	45	50	55	0
Concentration (mg/l)	175	200	225	250	275	0
Turbidity (NTU)	13.3	4.13	2.24	3.87	4.76	404
Temperature (^{0}c)	20	20	20	20	20	20
PH	7.4	7.4	7.4	7.4	7.4	7.6
Conductivity (μS/cm)	149	156.7	161.6	166.4	170.9	132
TDS (mg/l)	94	99.8	101.8	105.5	107.6	82.8
Alkalinity (mg/L as CaCO3)	-	-	40	-	-	37.6
SVI (mg/l)	-	-	30	-	-	-
Observation:						

11-10-2012	**Treated Water**					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume (ml)	35	40	45	50	55	0
Concentration (mg/l)	175	200	225	250	275	0
Turbidity (NTU)	13.6	4.24	2.03	3.38	4.32	404
Temperature (^{0}c)	-	-	20	-	-	20
PH	-	-	7.5	-	-	7.6
Conductivity (μS/cm)	-	-	162.4	-	-	-
TDS (mg/l)	-	-	102.3	-	-	-
Alkalinity (mg/L as CaCO3)	-	-	41	-	-	-
SVI (mg/l)	-	-	29	-	-	-
Observation:						

11-10-2012	**Treated Water**					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume (ml)	35	40	45	50	55	0
Concentration (mg/l)	175	200	225	250	275	0
Turbidity (NTU)	12.9	4.04	2.12	3.85	4.5	403.2
Temperature (^{0}c)	-	-	20	-	-	20
PH	-	-	7.4	-	-	7.6
Conductivity (µS/cm)	-	-	161	-	-	-
TDS (mg/l)	-	-	102.3	-	-	-
Alkalinity (mg/L as CaCO3)	-	-	40.2	-	-	-
SVI (mg/l)	-	-	29	-	-	-
Observation:						

Coagulant – OFI
Raw water – From Geffersa Water Treatment Plant

1-11-2012	**Treated Water**					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume (ml)	8	10	12	14	16	0
Concentration (mg/l)	40	50	60	70	80	0
Turbidity (NTU)	10.4	4.27	2.61	3.6	5.97	61.2
Temperature (^{0}c)	20	20	20	20	20	20
PH	7.3	7.3	7.3	7.3	7.3	7.4
Conductivity (µS/cm)	86.1	87.9	90.4	93	95.4	74.4
TDS (mg/l)	54.2	55.5	57.2	58.6	60.1	47.6
Alkalinity (mg/L as CaCO3)	-	-	26.4	-	-	24
SVI (mg/l)	-	-	15	-	-	-
Observation:						

1-11-2012	**Treated Water**					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume (ml)	35	40	45	50	55	0
Concentration (mg/l)	175	200	225	250	275	0
Turbidity (NTU)	9.9	4.24	2.77	3.38	5.32	61
Temperature (^{0}c)	20	20	20	20	20	20
PH	-	-	7.3	-	-	7.4
Conductivity (µS/cm)	-	-	90.4	-	-	-
TDS (mg/l)	-	-	56.9	-	-	-
Alkalinity (mg/L as CaCO3)	-	-	27	-	-	-
SVI (mg/l)	-	-	15	-	-	-
Observation:						

1-11-2012	**Treated Water**					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume (ml)	35	40	45	50	55	0
Concentration (mg/l)	175	200	225	250	275	0
Turbidity (NTU)	10	4.04	2.54	3.85	5.5	61
Temperature (^{0}c)	20	20	20	20	20	20
PH	-	-	7.3	-	-	7.4
Conductivity (µS/cm)	-	-	89.5	-	-	-
TDS (mg/l)	-	-	56.3	-	-	-
Alkalinity (mg/L as CaCO3)	-	-	27	-	-	-
SVI (mg/l)	-	-	14	-	-	-
Observation:						

Appendix B: PolyDADMAC and Alum Jar test Result

Coagulant – PolyDADMAC
Coagulant aid – Polyacrylamide
Raw Water – From Legedadi Water treatment Plant

11-10-2012	**Treated Water**					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume PDADMAC (ml)	7	8	9	10	11	0
Concentration of PDADMAC (mg/l)	7	8	9	10	11	0
Added Volume Polyacrylamide (ml)	1	1	1	1	1	0
Concentration of Polyacrylamide (mg/l)	0.5	0.5	0.5	0.5	0.5	0
Turbidity (NTU)	7.74	4.84	3.76	2.1	2.97	403
Temperature (^{0}c)	20	20	20	20	20	20
PH	7.6	7.6	7.6	7.6	7.6	7.6
Conductivity (µS/cm)	131	131	131.2	131.3	131.6	131.6
TDS (mg/l)	82.5	82.5	83.2	82.7	83	83
Alkalinity (mg/L as CaCO3)	-	-	-	37.6	-	37.6
SVI (mg/l)	-	-	-	20	-	-

11-10-2012	**Treated Water**					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume PDADMAC (ml)	7	8	9	10	11	0
Concentration of PDADMAC (mg/l)	7	8	9	10	11	0
Added Volume Polyacrylamide (ml)	1	1	1	1	1	0
Concentration of Polyacrylamide (mg/l)	0.5	0.5	0.5	0.5	0.5	0
Turbidity (NTU)	7.49	5.03	3.47	2.1	3.12	403.3
Temperature (^{0}c)	20	20	20	20	20	20
PH	-	-	-	7.6	-	7.6
Conductivity (µS/cm)	-	-	-	131.3	-	-
TDS (mg/l)	-	-	-	82.7	-	-
Alkalinity (mg/L as CaCO3)	-	-	-	37.6	-	-
SVI (mg/l)	-	-	-	20	-	-

11-10-2012	**Treated Water**					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume PDADMAC (ml)	7	8	9	10	11	0
Concentration of PDADMAC (mg/l)	7	8	9	10	11	0
Added Volume Polyacrylamide (ml)	1	1	1	1	1	0
Concentration of Polyacrylamide (mg/l)	0.5	0.5	0.5	0.5	0.5	0
Turbidity (NTU)	7.7	4.67	3.4	1.9	3.33	403
Temperature (^{0}c)	20	20	20	20	20	20
PH	-	-	-	7.6	-	7.6
Conductivity (µS/cm)	-	-	-	131.2	-	-
TDS (mg/l)	-	-	-	82.5	-	-
Alkalinity (mg/L as CaCO3)	-	-	-	37.4	-	-
SVI (mg/l)	-	-	-	20	-	-

Coagulant – Alum
Coagulant Aid – Lime
Raw Water – from Geffersa Water treatment Plant

1-11-2012	**Treated Water**					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume Alum (ml)	3	4	5	6	7	0
Concentration of Alum (mg/l)	15	20	25	30	35	0
Added Volume Lime (ml)	5	6.7	8.3	10	11.7	0
Concentration of Lime (mg/l)	5	6.7	8.3	10	11.7	0
Turbidity (NTU)	6.9	5.2	2.7	2.4	4.3	61
Temperature (^{0}c)	20	20	20	20	20	20
PH	6.9	6.8	6.8	6.8	6.7	7.4
Conductivity (µS/cm)	80	80.3	81.2	82.4	83	74.4
TDS (mg/l)	50.4	50.6	51.1	51.9	52.2	46.9
Alkalinity (mg/L as CaCO3)	-	-	-	20	-	24
SVI (mg/l)	-	-	-	7	-	-

1-11-2012	**Treated Water**					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume Alum (ml)	3	4	5	6	7	0
Concentration of Alum (mg/l)	15	20	25	30	35	0
Added Volume Lime (ml)	5	6.7	8.3	10	11.7	0
Concentration of Lime (mg/l)	5	6.7	8.3	10	11.7	0
Turbidity (NTU)	6.9	5.3	2.6	2.4	4.1	61
Temperature (^{0}c)	20	20	20	20	20	20
PH	6.9	6.8	6.8	6.8	6.7	7.4
Conductivity (µS/cm)	-	-	-	81.8	-	74.4
TDS (mg/l)	-	-	-	51.5	-	46.9
Alkalinity (mg/L as CaCO3)	-	-	-	20.2	-	24
SVI (mg/l)	-	-	-	7	-	-

1-11-2012	**Treated Water**					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume Alum (ml)	3	4	5	6	7	0
Concentration of Alum (mg/l)	15	20	25	30	35	0
Added Volume Lime (ml)	5	6.7	8.3	10	11.7	0
Concentration of Lime (mg/l)	5	6.7	8.3	10	11.7	0
Turbidity (NTU)	6.67	5.2	2.91	2.31	4.3	61
Temperature (^{0}c)	20	20	20	20	20	20
PH	-	-	-	6.7	-	7.4
Conductivity (µS/cm)	-	-	-	82.3	-	74.4
TDS (mg/l)	-	-	-	51.9	-	46.9
Alkalinity (mg/L as CaCO3)	-	-	-	20.2	-	24
SVI (mg/l)	-	-	-	7	-	-

Appendix C: Moringa Olifera Jar test Result

Coagulant – Moringa Olifera
Raw water – From Legedadi Water treatment Plant

15-10-2012	**Treated Water**					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume (ml)	8	10	12	14	16	0
Concentration (mg/l)	80	100	120	140	160	0
Turbidity (NTU)	5.9	3.8	5.6	7.7	14.4	396
Temperature (^{0}c)	20	20	20	20	20	20
PH	7.5	7.5	7.5	7.5	7.5	7.6
Conductivity (μS/cm)	137.3	141.8	143.7	144.9	146.2	128.7
TDS (mg/l)	86.4	89.3	90.5	91.3	92.4	81
Alkalinity (mg/L as CaCO3)	-	-	35.6	-	-	-
SVI (mg/l)	-	-	20	-	-	-

15-10-2012	**Treated Water**					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume (ml)	35	40	45	50	55	0
Concentration (mg/l)	80	100	120	140	160	0
Turbidity (NTU)	6.8	4.72	6.1	7.25	13.95	395
Temperature (^{0}c)	20	20	20	20	20	20
PH	-	-	7.5	-	-	7.6
Conductivity (μS/cm)	-	-	142.7	-	-	-
TDS (mg/l)	-	-	89.9	-	-	-
Alkalinity (mg/L as CaCO3)	-	-	36	-	-	-
SVI (mg/l)	-	-	20	-	-	-

15-10-2012	**Treated Water**					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume (ml)	35	40	45	50	55	0
Concentration (mg/l)	80	100	120	140	160	0
Turbidity (NTU)	6.4	4.2	5.9	8.2	13.8	395
Temperature (^{0}c)	20	20	20	20	20	20
PH	-	-	7.5	-	-	7.6
Conductivity (µS/cm)	-	-	142.8	-	-	-
TDS (mg/l)	-	-	89.9	-	-	-
Alkalinity (mg/L as CaCO3)	-	-	36	-	-	-
SVI (mg/l)	-	-	20	-	-	-

Coagulant – Moringa Olifera
Raw water – From Geffersa Water treatment Plant

8-11-2012	**Treated Water**					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume (ml)	3	4	5	6	7	0
Concentration (mg/l)	20	30	40	50	60	0
Turbidity (NTU)	10.7	8.3	16.1	17.5	22.3	55.6
Temperature (^{0}c)	20	20	20	20	20	20
PH	7.3	7.3	7.3	7.3	7.3	7.4
Conductivity (µS/cm)	-	77.4	-	-	-	71.8
TDS (mg/l)	-	48.7	-	-	-	45.3
Alkalinity (mg/L as CaCO3)	-	23.4	-	-	-	24
SVI (mg/l)	-	6	-	-	-	

8-11-2012	**Treated Water**					
Jar number	1	2	3	4	5	Blank
Added Volume (ml)	3	4	5	6	7	0
Concentration (mg/l)	20	30	40	50	60	0
Turbidity (NTU)	10.2	8.6	15.5	18	21.8	56
Temperature (^{0}c)	20	20	20	20	20	20
PH	-	7.3	-	-	-	7.4
Conductivity (µS/cm)	-	78.8	-	-	-	-
TDS (mg/l)	-	49.6	-	-	-	-
Alkalinity (mg/L as CaCO3)	-	23.8	-	-	-	-
SVI (mg/l)	-	6	-	-	-	-

8-11-2012	**Treated Water**					
Jar number	1	2	3	4	5	Blank
Added Volume (ml)	3	4	5	6	7	0
Concentration (mg/l)	30	40	50	60	70	0
Turbidity (NTU)	11	8.1	16	17.3	21.2	56
Temperature (^{0}c)	20	20	20	20	20	20
PH	-	7.3	-	-	-	7.4
Conductivity (µS/cm)	-	78.5	-	-	-	-
TDS (mg/l)	-	49.4	-	-	-	-
Alkalinity (mg/L as CaCO3)	-	23.8	-	-	-	-
SVI (mg/l)	-	6	-	-	-	-

Appendix D: OFI as a coagulant aid

Coagulant – Alum
Coagulant Aid – OFI
Raw water – From Geffersa Water treatment Plant

3-11-2012	**Treated Water**					
Jar number	1	2	3	4	5	Blank
Added Volume Alum (ml)	2	4	6	8	10	0
Concentration of Alum (mg/l)	2	4	6	8	10	0
Added Volume Cactus (ml)	3	3	3	3	3	0
Concentration of Cactus (mg/l)	15	15	15	15	15	0
Turbidity (NTU)	11.5	11.4	9.8	10.8	13.1	56
Temperature (^{0}c)	20	20	20	20	20	20
PH	-	-	6.9	-	-	7.4
Conductivity (µS/cm)	-	-	86.4	-	-	71.8
TDS (mg/l)	-	-	54.4	-	-	45.2
Alkalinity (mg/L as CaCO3)	-	-	19.6	-	-	24
SVI (mg/l)	-	-	5	-	-	-

3-11-2012	**Treated Water**					
Jar number	1	2	3	4	5	Blank
Added Volume Alum (ml)	2	4	6	8	10	0
Concentration of Alum (mg/l)	2	4	6	8	10	0
Added Volume Cactus (ml)	3	3	3	3	3	0
Concentration of Cactus (mg/l)	15	15	15	15	15	0
Turbidity (NTU)	12	11.1	9.8	10.5	13.8	56
Temperature (^{0}c)	20	20	20	20	20	20
PH	-	-	6.8	-	-	7.4
Conductivity (µS/cm)	-	-	87.3	-	-	-
TDS (mg/l)	-	-	54.9	-	-	-
Alkalinity (mg/L as CaCO3)	-	-	19.2	-	-	-
SVI (mg/l)	-	-	5	-	-	-

3-11-2012	**Treated Water**					
Jar number	1	2	3	4	5	Blank
Added Volume Alum (ml)	2	4	6	8	10	0
Concentration of Alum (mg/l)	2	4	6	8	10	0
Added Volume Cactus (ml)	3	3	3	3	3	0
Concentration of Cactus (mg/l)	15	15	15	15	15	0
Turbidity (NTU)	11.5	11.7	9.1	10.6	13.8	56
Temperature (^{0}c)	20	20	20	20	20	20
PH	-	-	6.8	-	-	7.4
Conductivity (μS/cm)	-	-	86.9	-	-	-
TDS (mg/l)	-	-	54.7	-	-	-
Alkalinity (mg/L as CaCO3)	-	-	19.2	-	-	-
SVI (mg/l)	-	-	5	-	-	-

Coagulant – Moringa Olifera
Coagulant Aid – OFI
Raw Water – From Legedadi Water treatment Plant

15-10-2012	**Treated Water**					
Jar number	1	2	3	4	5	Blank
Added Volume Moringa (ml)	3	4	5	6	7	0
Concentration of Moringa (mg/l)	20	30	40	50	60	0
Added Volume Cactus (ml)	8	8	8	8	8	0
Concentration of Cactus (mg/l)	40	40	40	40	40	0
Turbidity (NTU)	4.73	2.9	3.41	5.94	6.35	396
Temperature (^{0}c)	20	20	20	20	20	20
PH	7.5	7.5	7.5	7.5	7.4	7.6
Conductivity (µS/cm)	141.1	142.7	144.6	146	147.5	128.7
TDS (mg/l)	89.4	89.9	91	91.9	92.8	81
Alkalinity (mg/L as CaCO3)	-	-	37	-	-	37.6
SVI (mg/l)	-	-	15	-	-	-

15-10-2012	**Treated Water**					
Jar number	1	2	3	4	5	Blank
Added Volume Moringa (ml)	3	4	5	6	7	0
Concentration of Moringa (mg/l)	30	40	50	60	70	0
Added Volume Cactus (ml)	8	8	8	8	8	0
Concentration of Cactus (mg/l)	40	40	40	40	40	0
Turbidity (NTU)	5.1	2.67	3.32	6.2	7.1	395
Temperature (^{0}c)	20	20	20	20	20	20
PH	-	-	7.5	-	-	7.6
Conductivity (µS/cm)	-	-	145.9	-	-	-
TDS (mg/l)	-	-	91.9	-	-	-
Alkalinity (mg/L as CaCO3)	-	-	37.4	-	-	-
SVI (mg/l)	-	-	15	-	-	-

`15-10-2012	**Treated Water**					
Jar number	1	2	3	4	5	Blank
Added Volume Moringa (ml)	3	4	5	6	7	0
Concentration of Moringa (mg/l)	30	40	50	60	70	0
Added Volume Cactus (ml)	8	8	8	8	8	0
Concentration of Cactus (mg/l)	40	40	40	40	40	0
Turbidity (NTU)	4.6	2.48	3.01	6.3	6.68	395
Temperature (^{0}c)	20	20	20	20	20	20
PH	-	-	7.5	-	-	7.6
Conductivity (µS/cm)	-	-	145.6	-	-	-
TDS (mg/l)	-	-	91.7	-	-	-
Alkalinity (mg/L as CaCO3)	-	-	36.6	-	-	-
SVI (mg/l)	-	-	15	-	-	-

Coagulant – Moringa Olifera
Coagulant Aid – OFI
Raw Water – From Geffersa Water Treatment Plant

8-11-2012	**Treated Water**					
Jar number	1	2	3	4	5	Blank
Added Volume Moringa (ml)	0.5	1	1.5	2	2.5	0
Concentration of Moringa (mg/l)	5	10	15	20	25	0
Added Volume Cactus (ml)	2	2	2	2	2	0
Concentration of Cactus (mg/l)	10	10	10	10	10	0
Turbidity (NTU)	5.3	2.7	2.2	3.4	3.76	55
Temperature (^{0}c)	20	20	20	20	20	20
PH	7.3	7.3	7.3	7.3	7.3	7.4
Conductivity (µS/cm)	-	-	81.4	-	-	71.8
TDS (mg/l)	-	-	51.2	-	-	45.3
Alkalinity (mg/L as CaCO3)	-	-	24	-	-	24
SVI (mg/l)	-	-	5	-	-	-

8-11-2012	**Treated Water**					
Jar number	1	2	3	4	5	Blank
Added Volume Moringa (ml)	0.5	1	1.5	2	2.5	0
Concentration of Moringa (mg/l)	5	10	15	20	25	0
Added Volume Cactus (ml)	2	2	2	2	2	0
Concentration of Cactus (mg/l)	10	10	10	10	10	0
Turbidity (NTU)	5.7	2.7	2.3	3.3	4.1	55
Temperature (^{0}c)	20	20	20	20	20	20
PH	-	-	7.3	-	-	7.4
Conductivity (µS/cm)			80.7			
TDS (mg/l)			50.8			
Alkalinity (mg/L as CaCO3)			24			
SVI (mg/l)			5			

8-11-2012	**Treated Water**					
Jar number	1	2	3	4	5	Blank
Added Volume Moringa (ml)	0.5	1	1.5	2	2.5	0
Concentration of Moringa (mg/l)	5	10	15	20	25	0
Added Volume Cactus (ml)	2	2	2	2	2	0
Concentration of Cactus (mg/l)	10	10	10	10	10	0
Turbidity (NTU)	5.7	2.7	2.3	3.3	4.1	55
Temperature (^{0}c)	20	20	20	20	20	20
PH	-	-	7.3	-	-	7.4
Conductivity (µS/cm)			80.7			
TDS (mg/l)			50.8			
Alkalinity (mg/L as CaCO3)			24			
SVI (mg/l)			5			

Appendix E: Factors affecting OFI coagulation efficiency

Initial Turbidity – 10 NTU

20-10-2012	Treated Water					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume (ml)	1	1.5	2	2.5	3	0
Concentration (mg/l)	5	7.5	10	12.5	15	0
Turbidity (NTU)	2.07	1.37	1.46	1.57	2.03	10

20-10-2012	Treated Water					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume (ml)	1	1.5	2	2.5	3	0
Concentration (mg/l)	5	7.5	10	12.5	15	0
Turbidity (NTU)	1.9	1.33	1.5	1.6	2.07	10

20-10-2012	Treated Water					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume (ml)	1	1.5	2	2.5	3	0
Concentration (mg/l)	5	7.5	10	12.5	15	0
Turbidity (NTU)	1.99	1.43	1.5	1.8	2.03	10

Initial Turbidity – 30 NTU

20-10-2012	Treated Water					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume (ml)	3	4	5	6	7	0
Concentration (mg/l)	15	20	25	30	35	0
Turbidity (NTU)	2.03	1.88	1.37	1.49	1.6	30

20-10-2012	Treated Water					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume (ml)	3	4	5	6	7	0
Concentration (mg/l)	15	20	25	30	35	0
Turbidity (NTU)	2.44	2.1	1.34	1.57	1.67	30

20-10-2012	Treated Water					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume (ml)	3	4	5	6	7	0
Concentration (mg/l)	15	20	25	30	35	0
Turbidity (NTU)	2.5	1.97	1.44	1.6	1.87	29.6

PH
Turbidity – 30 NTU

21-10-2012	**Treated Water**					
Jar number	**1**	**2**	**3**	**4**	**5**	**6**
Added Volume (ml)	5	5	5	5	5	5
Concentration (mg/l)	25	25	25	25	25	25
PH	2	4	6	8	10	12
Turbidity (NTU)	3.7	4.88	5.7	1.3	0.96	1.35

21-10-2012	**Treated Water**					
Jar number	**1**	**2**	**3**	**4**	**5**	**6**
Added Volume (ml)	5	5	5	5	5	5
Concentration (mg/l)	25	25	25	25	25	25
PH	2	4	6	8	10	12
Turbidity (NTU)	3.1	4.87	5.1	1.41	1.1	1.4

21-10-2012	**Treated Water**					
Jar number	**1**	**2**	**3**	**4**	**5**	**6**
Added Volume (ml)	5	5	5	5	5	5
Concentration (mg/l)	25	25	25	25	25	25
PH	2	4	6	8	10	12
Turbidity (NTU)	3.3	5.03	5.3	1.37	1.1	1.33

Temperature 10^{0}c
Turbidity – 30 NTU

21-10-2012	**Treated Water**					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume (ml)	3	4	5	6	7	0
Concentration (mg/l)	15	20	25	30	35	0
Temperature	10	10	10	10	10	10
Turbidity (NTU)	4.63	4.38	3.37	3.69	4.27	30

21-10-2012	**Treated Water**					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume (ml)	3	4	5	6	7	0
Concentration (mg/l)	15	20	25	30	35	0
Temperature	10	10	10	10	10	10
Turbidity (NTU)	4.89	4.24	3.28	3.7	4.37	30

21-10-2012	**Treated Water**					
Jar number	**1**	**2**	**3**	**4**	**5**	**Blank**
Added Volume (ml)	3	4	5	6	7	0
Concentration (mg/l)	15	20	25	30	35	0
Temperature	10	10	10	10	10	10
Turbidity (NTU)	4.8	4.17	3.54	3.97	4.42	30