REMOVAL OF NATURAL ORGANIC MATTER AND CONTROL OF TRIHALOMETHANES FORMATION IN WATER TREATMENT

Herbert Mpagi Kalibbala

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Dedicated to my grandmother Yunia Mpagi
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## ACRONYMS AND ABBREVIATIONS

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<tr>
<th>Acronym</th>
<th>Abbreviation</th>
</tr>
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<tbody>
<tr>
<td>AWWA</td>
<td>American Water Works Association</td>
</tr>
<tr>
<td>CBP</td>
<td>Chlorination By-Product</td>
</tr>
<tr>
<td>D</td>
<td>Depth</td>
</tr>
<tr>
<td>DAF</td>
<td>Dissolved Air Flotation</td>
</tr>
<tr>
<td>DBP</td>
<td>Disinfection By-Product</td>
</tr>
<tr>
<td>DCE-UT</td>
<td>Department of Civil Engineering – University of Toronto</td>
</tr>
<tr>
<td>DGSM</td>
<td>Department of Geological Survey and Mines</td>
</tr>
<tr>
<td>DOC</td>
<td>Dissolved Organic Carbon</td>
</tr>
<tr>
<td>DON</td>
<td>Dissolved Organic Nitrogen</td>
</tr>
<tr>
<td>DPD</td>
<td>Diethyl-P-Phenylenediamine</td>
</tr>
<tr>
<td>EBCT</td>
<td>Empty Bed Contact Time</td>
</tr>
<tr>
<td>EC</td>
<td>Electrical Conductivity</td>
</tr>
<tr>
<td>EDS</td>
<td>Energy Dispersive Spectrometry</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>ES</td>
<td>Effective Size</td>
</tr>
<tr>
<td>GAC</td>
<td>Granulated Activated Carbon</td>
</tr>
<tr>
<td>GC</td>
<td>Gas Chromatography</td>
</tr>
<tr>
<td>GDP</td>
<td>Growth Domestic Product</td>
</tr>
<tr>
<td>HAA</td>
<td>Halo Acetic Acid</td>
</tr>
<tr>
<td>HAAFP</td>
<td>Halo Acetic Acid Formation Potential</td>
</tr>
<tr>
<td>HPLC</td>
<td>High Performance Liquid Chromatography</td>
</tr>
<tr>
<td>HPSEC</td>
<td>High Performance Size Exclusion Chromatography</td>
</tr>
<tr>
<td>HRF</td>
<td>Horizontal Roughing Filter</td>
</tr>
<tr>
<td>HRFP</td>
<td>Horizontal Roughing Filter with Pumice</td>
</tr>
<tr>
<td>ICP-MS</td>
<td>Inductively Coupled Plasma-Mass Spectrometry</td>
</tr>
<tr>
<td>MOC</td>
<td><em>Moringa oleifera</em> Coagulant</td>
</tr>
<tr>
<td>MOC-SC</td>
<td><em>Moringa oleifera</em> Coagulant extracted with Sodium Chloride</td>
</tr>
<tr>
<td>MOC-DW</td>
<td><em>Moringa oleifera</em> Coagulant extracted with Distilled Water</td>
</tr>
<tr>
<td>MW</td>
<td>Molecular Weight</td>
</tr>
<tr>
<td>NMR</td>
<td>Nuclear Magnetic Resonance</td>
</tr>
<tr>
<td>NOM</td>
<td>Natural Organic Matter</td>
</tr>
<tr>
<td>NTU</td>
<td>Nephelometric Turbidity Unit</td>
</tr>
<tr>
<td>NWSC</td>
<td>National Water and Sewerage Corporation</td>
</tr>
<tr>
<td>OCD</td>
<td>Organic Carbon Detector</td>
</tr>
<tr>
<td>OND</td>
<td>Organic Nitrogen Detector</td>
</tr>
<tr>
<td>OP</td>
<td>Original Pumice</td>
</tr>
<tr>
<td>PAC</td>
<td>Powdered Activated Carbon</td>
</tr>
<tr>
<td>PACl</td>
<td>Poly Aluminium Chloride</td>
</tr>
<tr>
<td>SDS–PAGE</td>
<td>Sodium Dodecyl Sulphate - Poly Acrylamide Gel Electrophoresis</td>
</tr>
<tr>
<td>SEC</td>
<td>Size Exclusion Chromatography</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Micrograph</td>
</tr>
</tbody>
</table>
SUVA  Specific Ultra Violet Absorbance
THM   Trihalomethane
THMFP Trihalomethane Formation Potential
TOC   Total Organic Carbon
TTHM Total Trihalomethanes
UC    Uniformity Coefficient
UF    Ultra Filtration
UNICEF United Nations Children’s Fund
USD   United States Dollar
UVA   Ultraviolet Absorbance
UVD   Ultraviolet Detector
VRF   Vertical flow Roughing Filter
XRD   X-ray Diffraction
WHO   World Health Organisation
BWTP  Boma Water Treatment Plant
List of Papers Appended


Other articles not appended in this thesis


ABSTRACT
Volcanic ash, pumice and *Moringa oleifera* (*M. oleifera*) were investigated as indigenous materials for removal of natural organic matter (NOM) at Kampala and Masaka water treatment plants in Uganda. Coagulation and filtration experiments were done using raw water at Kampala (Ggaba) and Masaka (Boma) National Water & Sewerage Corporation water treatment plants. Assessment of the two plants was done and they were found to be faced with differing challenges given the nature of their raw water sources. Therefore, the study was conducted to seek appropriate treatment processes that suit the conditions at the respective plant and avoid or minimize formation of unwanted chlorination by-products. The results from the study indicated that there were both operational and design handicaps at the Ggaba treatment plant with a need to modify the filtration and clarification units. At Masaka, pre-chlorination led to increases in total trihalomethanes as high as 4000%. The characterization studies indicated the major fraction of NOM to be hydrophilic and there was no variation in the character of NOM along the unit treatment processes investigated. On the other hand experiments conducted at both the pilot and laboratory scale gave promising results. Simple horizontal flow roughing filter at Masaka gave rise to dissolved organic carbon (DOC) and ferrous iron removals of 27% and 89% respectively. With a combined use of pumice and hydrogen peroxide in the filter, DOC removals of up to 68% were achieved. The results from jar test experiments also indicated that use of alum with *M. oleifera* coagulant extracted with sodium chloride solution as coagulant aid is promising as a first stage in the treatment train for waters with a humic materials and high content of iron, typical of swamp water sources. Therefore the findings show that it is possible to avoid the formation of unwanted by-products by application of roughing filtration with hydrogen peroxide in place of the pre-chlorination process. Assessment of the characteristics of the volcanic ash showed that it meets the requirements for a filtration material; and results obtained from the pilot study showed that it was a suitable alternative material for use in a dual media filtration system. There was an increase in the filter run length of about two and half fold in the dual media filtration column compared to the mono medium column.

Keywords: Water treatment, pumice, roughing filtration, trihalomethanes, coagulant aid, volcanic ash
Vulkanaska, pimpsten och Moringa oleifera (M. oleifera) undersökses som inhemska material för borttagande av naturligt organiskt material (NOM) i Kampala och Masaka reningsverk i Uganda. Koagulation och filtreringsexperiment gjordes med hjälp av råvatten i Kampala (Ggaba) och Masaka (Boma)reningsverk, som ingår i Nationella Vatten- och avloppsreningsverk, ett företag i Uganda. En bedömning av de två anläggningarna gjordes och det visade sig stå inför olika utmaningar på grund av de olika råvattnens karaktär. Den här studien genomfördes för att söka lämpliga processer för behandling av anpassade till förhållanden vid respektive anläggning samt för att undvika eller minimera uppkomsten av olika klorerade biprodukter. Resultatet från studien visade att det fanns problem både när det gäller design och arbetsrutiner på reningsverket Ggaba med ett behov att ändra filtrerings- och klarningsenheterna! Masaka ökade förkloreringsprocessen den totala mängden trihalometaner med 4000 %.

Karakteriseringen av naturligt organiskt material (NOM) visade på en stor andel hydrofilt material och att ingen förändring av det organiska materialets karakter skedde längs den undersökta processenheten. Å andra sidan visade både laboratorieförsök och experiment i pilotanläggningen att lovande resultat. Ett enkelt horisontellt flöde genom ett grovt filter i pilotanläggningen i Masaka resulterade i 89% mindre järn och 27% mindre NOM. Med en kombination av pimpsten och väteperoxid i filtret var avlägsnandet av löst organiskt material (DOC) från vattnet 68%. Resultaten från batchexperiment (jar test) i laboratoriet visade också lovande resultat för aluminium tillsammans med en koagulant extraherad med natriumklorid från Moringa oleifera (MOC-SC), som ett första steg för vatten från sumpmark med höga halter av järn och organiskt material. Således visar resultaten att det går att undvika bildandet av höga halter av trihalometan (THM) genom genom tillämpning av grovfiltrering med väteperoxid i stället för förkloreringsprocessen. Utvärderingen av vulkanaskans egenskaper visade att vulkanaskan uppfyller kraven på ett filtermaterial och resultaten från pilotanläggningen visade att det är ett lämpligt material i ett filtreringssystem med två media. Den utnyttjade delen av filtret var 2,5 gånger längre i köringen med dubbla medier jämfört med ett medium.

Nyckelord: Vattenrening, pimpsten, grovfiltrering, trihalometaner, koaguleringsmedel, vulkanaska
1. INTRODUCTION

1.1. Background

Access to safe drinking water is important as a health and development issue at national, regional and local levels. In some parts of the world, it has been shown that investments in water supply and sanitation can yield a net economic benefit, since the reductions in adverse health effects and health care costs outweigh the costs of undertaking the interventions (WHO, 2004a). The World Health Organization (WHO) estimates that for each USD 1 invested, returns ranging from USD 3- USD 34 can be achieved depending on the region and technology. At household level, almost two in three people that lack access to safe drinking water survive on less than USD 2 a day and one in three on less than USD 1 a day. In Sub-Saharan Africa, poverty remains high with almost 50 percent of the population living below the absolute poverty line of USD 1.25 per day whereas as much as 75 percent of the overall population below USD 2 per day. This indicates how difficult it is to improve safe water coverage through household investments. Consequently, the overall economic loss in Africa alone due to lack of access to safe water and basic sanitation is estimated at USD 28.4 billion a year, or around 5% of growth domestic product.

In urban areas, the exploding population growth creates unprecedented challenges, among which lack of access to safe water and sanitation have been the most pressing and painfully felt. Urban growth is most rapid in the developing world, where cities gain an average of 5 million residents every month. The rapid population growth has stressed existing water supply systems. This is accompanied by the sustainability of operation and maintenance of water supply infrastructure that has hindered access to water by the poor in many developing countries. 884 million people – 37% of whom live in Sub-Saharan Africa – still use unimproved sources for drinking-water (WHO/ UNICEF, 2010). And in cities, the urban poor pay up to 50 times more for a litre of water than their richer neighbours, since they often have to buy their water from private vendors (WHO/ UNICEF, 2010). The situation is again aggravated by deterioration of the quality of water resources, attributed to the direct and indirect effects of climate change, direct industrial and municipal waste discharge rendering existing treatment units ineffective to meet the water quality standards, both on a national and WHO level. Periods of drought followed by runoff during episodes of heavy precipitation concentrate contaminants and increase nutrient loads to water sources. The increase in nutrients again impacts on the type and quantity of organic matter that may act as disinfection or chlorinated by-product precursors. The end result is large consumption of imported chemicals like alum and chlorine used in the treatment of water rendering water expensive.

In addition, chemicals like alum have been associated with health problems and chlorine reacts with natural organic materials (NOM) during pre- and post-chlorination to form chlorination by-products some of which have been reported to have adverse health impacts (Amy et al., 1988; Arruda & Fromm, 1989; Dodds et al., 1999; Barrett et al., 2000; Yang et al., 2000; Gunten et al., 2001; Ivancev et al., 2002; Cedergren et al., 2002; Westerhoff et al., 2004). Although the risks to health from these by-products are extremely small in comparison with the risks associated with inadequate disinfection (WHO, 2011), efforts should be made to avoid the formation of disinfection or chlorination by-products by application of cost effective and appropriate technologies. Utilities, especially in the developing world, need to investigate other treatment options that can be integrated into conventional treatment train to still manage production of water of desired quality despite increasing contaminant levels at the source water.

1.2. Motivation

Uganda is endowed with various categories of freshwater water resources including rivers flowing through wetlands or swamps, groundwater and lakes. These sources contain varying amounts of organic sub-
stances arising from anthropogenic pollution and/ or overland runoff or leaching. However, most treatment plants in the country use chlorine as an oxidant for iron removal or as disinfectant but less or no attention is paid to the impact it has on the final water quality. Chlorine is known to react with NOM to form chlorination by-products, which are believed to be carcinogenic. It was on this basis that this research was conducted to seek appropriate treatment processes that suite the conditions at hand and avoid or minimize formation of unwanted by-products.

1.3. Case Study Areas

The study was carried out at Boma and Ggaba II water treatment plants located in Masaka Municipality and Kampala City respectively (Fig. 1). These plants are under the management of National Water & Sewerage Corporation (NWSC) an entity responsible for provision of piped water and sewerage services in the major urban centres in Uganda. Both areas are located within the Lake Victoria Basin along the Equator and as such experience a tropical climate. The average annual rainfall is 1100 – 1250 mm. The distribution of rainfall in a year follows a bimodal pattern with peaks in March – April (principal peak) and September – November (minor peak). This rainfall pattern is punctuated with two dry spells in January – February and June – July. Ggaba II is one of the plants that supply to Kampala, the others being Ggaba I (the oldest) and Ggaba III (the most recent). Kampala is the capital city of Uganda. The plants are located about 11 km South East of Kampala, at the shores of Lake Victoria. The three plants abstract water from the Inner Murchison Bay of Lake Victoria which also doubles as the drainage sink for the City. Masaka municipality is also supplied by two plants, Boma and Bwala (commissioned in 1959). Masaka waterworks are located 5 km from the municipality. The municipality is located in Bukoto county of Masaka District, in the southern part of Uganda west of Lake Victoria. It is situated about 125 km south of the capital city Kampala, along two trans-African highways to Rwanda and the Democratic Republic of Congo in the south-west and to the Republic of Tanzania in the south. Average altitude ranges from 1212 – 1303 m above sea level with the lowest altitude being the Nakayiba and Nabajjuzi valleys at 1212 m (UN-Habitat, 2010). There are two major wetlands in Masaka municipality, the Nabajjuzi and Nakayiba
wetlands in the central and western parts of the Municipality respectively. The Nabajuizi River is the main source of water for the Municipality, while Nakayiba wetland serves as a purifier for the Municipal Council sewerage system.

1.4. Aim of the Thesis

The purpose of the study was to investigate appropriate methods for NOM removal during drinking water treatment with minimal generation of trihalomethanes (THMs). This is because most water treatment plants, especially in the developing world, apply chlorine as an oxidant to oxidize iron at pre-treatment level and also as a disinfectant. Investigations were made on the use of indigenous materials like *Moringa oleifera* (*M. Oleifera*), volcanic ash and pumice to remove NOM and iron to avoid or minimise the formation of unwanted by-products in the final or treated water. Therefore, the main goals of this thesis were to:

i) Assess the existing NOM removal processes with the intention of identifying inherent problems during their application in the field

ii) Monitor formation of THMs from different treatment stages

iii) Test performance of *M. oleifera* in the removal of NOM and iron

iv) Assess the possibility of using pumice and volcanic ash as filter media in the removal of NOM

v) Assess the impact of hydrogen peroxide on the performance of pumice as filter media.

More specific aims in particular papers are presented in Table 1.

2. NATURAL ORGANIC MATTER (NOM): CHARACTERISTICS AND REMOVAL METHODS

2.1. Introduction

NOM is abundant in natural water resources and in many ways affect unit operations in water treatment. It is commonly used to describe the complex matrix of organic material in both dissolved and particulate form that occurs ubiquitously in both surface water and groundwater. It can be highly variable, depending on its source and extent of degradation (Owen et al., 1995; US EPA, 2001). Besides native flora and fauna, its composition is influenced by temperature, rainfall/humidity, light, microbial populations and geographic location. Its characteristics will vary depending on its origin (vegetation, soil, wastewater, agricultural return). Although NOM is considered harmless, it has been recognised as a chlorination by-product (CBP) precursor during the chlorination process and may result in bio-fouling of water distribution pipelines (Malcolm, 2007). In this section, the classification, characterisation methods and removal methods of NOM are presented together with its reactivity in water sources and implications for drinking water treatment plants.
2.2. Properties of NOM

2.2.1. Classification of NOM

NOM can be classified as autochthonous or allochthonous. The fraction of organic matter that derives from the biota growing (algal and bacterial growth) within the water bodies is classified as autochthonous NOM (Hong et al., 2008). This source of organic matter is due to the excretion and decay of organisms including bacteria, algae and vascular plants. The external organic matter (allochthonous) enters the water stream from the watershed, and originates from degradation of terrestrial vegetation and soil leaching during runoff. NOM in lakes, reservoirs, and streams of moderate to high trophic status is often dominated by autochthonous material, whereas low-order rivers and streams usually carry more allochthonous NOM. Allochthonous NOM has large carbon-to-nitrogen ratios (near 100 to 1), is highly coloured, and has significant aromatic carbon content, whereas autochthonous NOM has lower carbon-to-nitrogen ratios (near 10 to 1), is almost colourless, and has low aromatic carbon content.

Apart from origin, NOM can be further subdivided into two classes of compounds, non-humic (hydrophilic) material and humic (hydrophobic) substances (Owen et al., 1995; Zazouli et al., 2007). Based on solubility under different pH conditions, the humic fraction is generally divided further into three classes of materials: fulvic acids, humic acids and humins. Fulvic and humic acids are referred to collectively as humic substances or humics. Fulvic acids are soluble in water under all pH conditions; humic acids are soluble at pH > 2 while humins are insoluble at all pH values (US EPA, 2001). Fulvic acids represent the most water-soluble fraction of humic material and contribute 90 percent of the dissolved humic substances in most natural waters (Malcolm, 1985). The molecular weight of fulvic acids typically ranges between 500 and 2000 Da (Thurman et al., 1982) while humic acids have molecular weights greater than 2000 Da. Humic molecules contain aromatic, carbonyl, carboxyl, methoxyl and aliphatic units, with the phenolic and carboxylic functional groups providing most of the protonation and metal complexation sites. Non-humic material may include hydrophilic acids, proteins, small molecules such as sugars and amino acids (Amy et al., 2001).

2.2.2. Characterisation of NOM

The character of the NOM is dependent on both the source from which it is derived and the chemical and biological degradation to which it has been subjected (Chow et al., 1999). Chemical characterization of NOM is complex but it provides an insight into treatment process applicability. Such characterization is important because it is the key to understanding, predicting and controlling the reactivity and removal of NOM at water treatment facilities. Due to the complexity of humic substances, many research efforts have been directed to: molecular-size distribution, functional group characterization, metal complexation, acidic properties and reactivity with oxidants like chlorine (Drewes & Summers, 2002). Techniques that have been successfully used to characterize humics in terms of molecular mass include ultracentrifugation methods, field flow fractionation, chromatographic methods like high performance liquid size exclusion chromatography (HPLC-SEC) coupled with dissolved organic carbon (DOC) detectors, light scattering and partial specific volumes. NOM is also sometimes fractionated based on its physical properties, such as polarity (relative retention on functionalized poly-resins) and ionisability. Aside from fractionation, another venue of characterization is to study properties of the bulk solution rather than individual chemical components. Determination of bulk properties include measurement of total organic carbon (TOC), DOC, ultraviolet absorbance often measured at 254 nm (UV$_{254}$) and determination of specific UV absorbance (SUVA) as UV$_{254}$ divided by DOC. In addition to these, fractionation of the organic carbon into its hydrophobic and hydrophilic components can be done (Singer 2001). Other methods include structural characterization studies that make use of resins XAD-8 and XAD-4 (Leenheer, 2004;
Eikebrokk et al., 2006); nuclear magnetic resonance (NMR) or gas chromatography. NMR is and has been used extensively (Hatcher et al., 1980; Aluwihare et al., 1997; Haiber et al., 2001; Dria et al., 2002; Kujawinski et al., 2004) to estimate the relative contributions of functional groups such as aliphatic and aromatic moieties. Another important property of NOM is its molecular weight or molecular size distribution (Amy, 2004). Molecular weight fractionation is commonly achieved by ultra filtration (UF) or size exclusion chromatography (SEC). Unlike the fractionation with resins, the nature of NOM is preserved with UF and SEC as they do not require any use of chemicals like acids or bases. SEC can be used for more specific studies on NOM and its removal by using on-line detectors for ultraviolet absorbance, fluorescence and DOC. SEC coupled with UV detection has been widely used in determination of NOM molecular weight but since the ultraviolet detection is effective for humic substances and less effective for non-humic components such as proteins and polysaccharides, an online organic carbon detector was interfaced with SEC to permit recognition of all components, an approach known as liquid chromatography – organic carbon detection (LC-OC D) or size exclusion chromatography (Amy, 2004).

**Liquid chromatography – organic carbon detection (LC-OC D)**

NOM is fractionated into compounds based on their molecular weights which are then detected with a customised organic carbon detector (OCD). It is a non-destructive technique that does not require any sample pre-treatment. Additional ultraviolet absorbance detector (UVD) and the organic nitrogen detector (OND) provide more additional information. This technique gives both quantitative and qualitative information about the NOM. The quantitative part involves determination of carbon mass like DOC while the qualitative results give the molecular size distribution. The water sample is injected into a column with a chromatographic gel material. Substances with small molecular sizes can access more of the internal pore volume than those with larger sizes. Therefore, large molecules elute first followed by the smaller compounds. In addition to the organic carbon detector, LC-OC D uses ultraviolet detection and determination of the spectral adsorption coefficient at 254 nm to complete the information about the analysed water sample. It enables identification of seven fractions as presented in Table 2. Recently, additional detectors have been made available and they include ultraviolet absorbance detectors at 210 nm, 230 nm and 280 nm.

### Table 2: Fractions that can be identified by LC-OC D.

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biopolymers</td>
<td>This fraction has a high molecular weight distribution (MWD) of &gt; 50,000 – 2,000,000 g/mol. It does not absorb ultraviolet radiation and is hydrophilic. It is associated with polysaccharides, amino sugars or acids, polypeptides and proteins.</td>
</tr>
<tr>
<td>Humic substances</td>
<td>MWD: 100 – 10,000 g/mol; mainly consists of humic and fulvic acids</td>
</tr>
<tr>
<td>Building blocks</td>
<td>MWD: 350 – 500 g/mol; these are a result of hydrolysis of humic substances. They are intermediates in degradation of fulvic acids to low molecular weight organic acids and are difficult to remove by the flocculation process.</td>
</tr>
<tr>
<td>Low molecular weight organic acids and humic substances</td>
<td>These are final degradation products of NOM. They are released by algae and bacteria.</td>
</tr>
<tr>
<td>Low molecular weight neutrals</td>
<td>These are slightly hydrophobic substances and may include alcohols, aldehydes, ketones and amino acids.</td>
</tr>
<tr>
<td>Hydrophobic compounds</td>
<td>These compounds have sizes greater than 1µm. They are presented as a difference between TOC and summation of the chromatographic fractions of TOC. This fraction is not detectable by chromatography and consists probably of natural lipids, hopanoids and lipids.</td>
</tr>
<tr>
<td>Inorganic colloids</td>
<td>Inorganic colloids are negatively charged and greater than 1µm in size. They include neutral polyhydroxides and oxihydrates of iron (Fe), aluminium (Al) and silicone (Si).</td>
</tr>
</tbody>
</table>
2.2.3. Reactivity of NOM

Because different components of NOM have different reactivity with oxidants, knowledge of the reactivity of the different components with aqueous chlorine and bromine is central to understanding how to control CBPs in water treatment processes. The fraction of NOM designated as humic substances has historically been considered the most important with respect to its chemical properties and implications for water treatment (Drewes & Summers, 2002). The nature and extent of interaction between NOM components and aqueous chlorine species depend on numerous factors. Because pH influences electron distribution within NOM structures and the distribution of aqueous chlorine species, it is an important factor in the interaction between NOM and aqueous chlorine species. At drinking water pH levels, aqueous halogens occur as acids, for example, as hypochlorite (HOCl), hypobromite (HOBr) or anions like OCl\(^-\), OBr\(^-\) that react with NOM to produce organic-halide compounds. The kinetic competition between hydrolysis, oxidation and halogenation reactions also establishes pH as an important factor in determining the distribution of DBPs formed. In addition, some NOM components react with aqueous chlorine species at a much faster rate than other components. Therefore, chlorine dose and contact time are also important variables in determining the rate and extent of reaction between NOM and aqueous chlorine species. Temperature is also an important variable in this interaction. Rates of THMs formation have been found to increase with increasing temperatures (El-Shahat et al., 2001; Hellur-Grossman et al., 2001).

In addition to reacting with oxidants, NOM has various effects on metal speciation in aquatic systems. It is capable of complexing metals thus increasing metal solubility. It can also alter the distribution between reduced and oxidized forms of metals, reduce metal toxicity and alter metal availability to aquatic life. It influences the extent to which metals are adsorbed on suspended matter and affects the stability of metal-containing colloids. The attractive forces between metal ions and soluble, colloidal or particulate organic material range from weak physical adsorption (ions are easily replaceable) to strong metal chelating by weak physical adsorption (ions are indistinguishable from chemical bonds). Factors that affect NOM complexing of metals are pH, ionic strength, NOM source characteristics and competing ligands. Humic substances can be important metal complexing agents and may also significantly coat the solid mineral controlling the electrochemistry of the solid phase. Mechanisms involved are physical adsorption, electrostatic attraction, hydrogen bonding and co-ordination complexes. Where the solid phase, for example, clay and humic substances are similarly charged, adsorption may be facilitated by bridging associated with the polyelectrolyte. For instance, the transformation of Fe (II) and Fe (III) has significant effects on many natural processes. Ferric hydr(oxide) formation caused by changes of redox potentials has an impact on the distribution of trace metals and organic compounds through adsorption and co-precipitation. While hydrogen ion (H\(^+\)) competes with metal ions for anionic binding sites on fulvic acids, the hydroxyl ion (OH\(^-\)) competes with fulvic acids for the cationic metal ions. With increasing pH the availability of fulvic acid for complexing therefore increases whereas the availability of the metal ion decreases. Consequently, an intermediate pH most favours complexation between fulvic acids and metal ions.

Organic matter arising from algae is the most problematic fraction of autochthonous NOM to drinking water treatment. Apart from filter clogging and production of toxins, other deleterious effects of algae include production of taste and odour in the water, development of anoxic conditions, increased concentration of soluble and biodegradable organics in the water, and increased difficulties associated with filter cleaning (Ellis, 1985). Algae may also be a source of CBPs after chlorination (Hoehn et al., 1980; Widrig et al., 1996; Henderson et al., 2005) but algal cells as well as the algal extracellular organic matter showed a less or similar CBP
yield per unit concentration of organic carbon as compared with humic substances (Graham et al., 1998; Plummer & Edzwald, 2001). In this regard, the major concern lies in the fact that algal-derived organic matter is less easily removed by coagulation and filtration.

2.3. Removal methods of NOM

2.3.1. Introduction

Methods for removal of NOM range from conventional to advanced processes like membrane filtration, reverse osmosis, oxidation using ozone and/or hydrogen peroxide, combination of ultra violet radiation with hydrogen peroxide, etc. Adsorption processes that employ activated carbon or various resins can also be used to remove some types of NOM before chlorination or disinfection. In this subsection, a summary of methods for the removal of NOM is presented. Sometimes depending on the quality of the raw water, pre-treatment may be required before the conventional or advanced processes. Therefore, the various kinds of pre-treatment methods that have been applied for NOM removal are also presented.

2.3.2. Coagulation

For many years, the most common design for water treatment plants consisted of coagulation followed by flocculation, settling, and filtration. This eventually became known as ‘conventional’ treatment. Coagulation, flocculation and sedimentation, followed by rapid gravity sand filtration, are the key steps in conventional water treatment systems for NOM removal. The coagulation process, as operated in many water treatment plants, is in most cases optimized primarily for the removal of turbidity. Optimum conditions for removal of turbidity may differ from those for NOM. The coagulant demand is determined by the concentration of NOM provided the turbidity of the water is not excessive (Gregor et al., 1997). Therefore, it follows that the treatment process should be optimised for NOM removal where it is the major contaminant. However, its removal efficiency by coagulation will still vary depending on the physical and chemical characteristics of the water and the operating conditions.

**Coagulation for NOM removal**

The presence of NOM affects greatly the chemistry of coagulation. Coagulation-based processes induce its molecules to agglomerate so that they can be removed using clarification or filtration. The coagulation mechanisms include charge neutralisation, enmeshment or entrapment, complexing and adsorption whose operational conditions are not the same (Gregor et al., 1997). Each of the mechanism is favoured by a particular set of operational conditions although in practice, it is likely that these conditions will overlap and that more than one mechanism will be responsible for NOM removal. However, its different fractions also exhibit different properties in terms of treatability by coagulation with the high molecular weight, hydrophobic fractions reported to be efficiently removed while low molecular weight hydrophilic fractions are not easily removed (Eikebrokk et al., 2006).

According to Eikebrokk et al. (2006), the primary coagulation mechanisms for NOM are: 1) complexation with dissolved metal coagulant species (Al or Fe), leading to direct precipitation of a metal-NOM solid phase; 2) complexation with dissolved coagulant species, leading to adsorption of this complexed material onto precipitated metal hydroxide solids; and 3) direct adsorption onto the surface of precipitated metal hydroxide solids (sweep coagulation). The conceptual view of the coagulation reactions according to Pernitsky & Edzwald (2006) is presented in Figure 2.

Hydrolysing metal salts, based on aluminium (Al(III)) or iron (Fe(III)), are very widely used as coagulants. The high cationic charge makes them effective for destabilising NOM. These salts bring about destabilisation by adsorption and charge neutralisation as well as by particle entrapment (Duan & Gregory, 2003). An aluminium or iron based coagulant is added at the very beginning of the process. When a salt of Al(III) or Fe(III) is added to water, it dissociates to yield trivalent ions, which hydrate to form aquometal complexes
Al(H₂O)₆³⁺ and Fe(H₂O)₆³⁺. These complexes then pass through a series of hydrolytic reactions in which H₂O molecules in the hydration shell are replaced by hydroxyl ions (OH⁻) ions to form a variety of soluble species such as Al(OH)₂⁺. These products are quite effective as coagulants as they adsorb very strongly onto the surface of most negative colloids. Cationic aluminium or iron interacts electrostatically with anionic NOM to form insoluble charge-neutral products.

In regions of operation where insoluble aluminium or iron hydroxides form, NOM can be removed by entrapment or surface adsorption (sweep coagulation). In this case, the concentration of coagulant has to be high enough to cause rapid precipitation of the metal hydroxides, for example, Al(OH)₃. Colloidal NOM can also act as nuclei for precipitate formation, or can become entrapped during floc aggregation. However, the sweep coagulation strategy is unlikely to be effective for the removal of fulvic acids which are more soluble with higher anionic charge densities that facilitate their dissolution. Charge neutralisation mechanism may remove soluble fulvic acids but high doses of the coagulant may be required for complete neutralisation through a strategy known as enhanced coagulation.

Enhanced coagulation is the modification of the conventional coagulation process to achieve greater NOM removals (Tomaszewski et al., 2004). The US EPA defines enhanced coagulation as the process of improving the removal of disinfection by-product precursors in a conventional water treatment plant (US EPA, 1999). This strategy may be achieved by significantly increasing the dosages of coagulant and adjusting pH to optimum ranges (Liu et al., 2011). The process relies on exact dosing of coagulant to neutralize the charges that would usually keep particles at a distance from one another and it involves chemical interaction of soluble NOM with soluble coagulant metal ions such as aluminium (Gregor et al., 1997). According to Gregor et al. (1997), the metal cation and the chemically bound or complexed NOM remain in solution until either the binding capacity of the NOM has been satisfied, or the solubility of the metal-NOM complex is exceeded. The complex does not need to be charge-neutral to precipitate. Once the charges are neutralized, the particles are encouraged to agglomerate through flocculation and removed through clarification and/or filtration.

With respect to algae, coagulation and sedimentation can be effective for its

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**Fig. 2. A conceptual view of coagulation reactions (Eikekkbrok et al., 2006).**
removal, although care must be taken to remove these organisms without disrupting the cells, as this may release algal toxins into the treated water (WHO, 2004). Coagulation and sedimentation alone are not very effective at removing algal toxins; studies have shown removal levels ranging from 0 to 49%. However, addition of powdered activated carbon to the clarification process can increase removal levels to 90% or more, depending on the carbon dose, type of carbon, toxin level and organic matrix (Yoo et al., 1995). Using a natural coagulant, chitosan, algae (Chlorella and Scenedesmus quadricuda) removals of more than 90% were achieved at neutral to alkaline pH conditions (WHO, 2004).

Factors affecting and controlling NOM removal by coagulation

The effectiveness of NOM removal varies with its nature or character (molecular weight, charge density and polarity), the type of coagulant and with properties of the raw water (Tomaszewsh et al., 2004). In addition, rates of chemical dosing, mixing conditions, flocculation times, the selection of chemicals and their order of addition, can all affect performance. Performance of metal salts is significantly influenced by the pH and alkalinity of the solution. The charge on hydrolysis products and precipitation of metal hydroxides are both controlled by pH value. The optimum pH for the coagulation process varies with the choice of coagulant. The hydrolysis products possess a positive charge at pH values below iso-electric point of the metal hydroxide. Negatively charged species, which predominate above iso-electric point, are ineffective for the destabilization of negatively charged colloids. The solubility of aluminium and ferric hydroxides is minimal at a particular pH value and increases as the pH increases or decreases from that value. For aluminium sulphate it is usually 5.5 to 7.5, for ferric salts it is within the range of 5 to 8.5. The optimum pH will also vary with changing raw water characteristics. Kastl et al. (2008) further notes that the surface property of the floc changes with pH, with positive zeta potential at low pH and negative zeta potential at high pH. And what is seen as DOC removal during coagulation at different pH values is a combined effect of the change in the surface properties of both the floc and humic substances. For water with low alkalinity, coagulant addition can consume all the available alkalinity, depressing the pH to values too low for effective treatment, while high alkalinity water may require addition of a high coagulant dose to depress the pH to values favourable for coagulation. Alum and ferric chlorides are more acidic than poly aluminium chlorides, and therefore result in greater alkalinity requirement after addition. Aluminium sulphate and ferric chloride react with natural alkalinity in water as indicated in equation (1) and (2), respectively.

\[
\begin{align*}
\text{Al}_2(\text{SO}_4)_3\text{H}_2\text{O} + 6\text{HCO}_3^- & \rightarrow 2\text{Al(OH)}_3(s) + 6\text{CO}_2 + 14\text{H}_2\text{O} + 3\text{SO}_4^{2-} \quad (1) \\
\text{FeCl}_3 + 3\text{HCO}_3^- & \rightarrow \text{Fe(OH)}_3(s) + 3\text{CO}_2 + 3\text{Cl}^- \quad (2)
\end{align*}
\]

Generally, coagulation removes humic and high molecular weight organic matter better than non humic and low molecular weight organic matter and according to Uyak et al. (2007), the non humic fraction of NOM could be removed by using adsorption process. However, in water with almost same fraction of humic and fulvic acids, high doses of coagulant required by soluble fulvic acids to neutralize the high anionic charge (enhanced coagulation) is likely to correspond to overdosing of humic acid colloids resulting in re-stabilisation of the colloids. It is therefore paramount to find alternative means of removing one fraction or to carry out the coagulation process in two steps. The results of NOM characterization techniques such as high performance SEC indicate that coagulation preferentially removes higher molecular weight ultraviolet absorbing compounds leaving lower molecular weight and less ultraviolet absorbing material in the treated water. Sequential coagulation treatment using repetitive doses of alum indicates that there is a portion of the organic material, known as recalcitrant NOM, which cannot be removed by coagulation regardless of the coagulant dose and conditions. The charged hydrophilic, very hydrophobic acid and slightly hydrophobic acid fractions are
the most amenable to removal by coagulation (Juhna & Melin, 2006). The higher the proportion of these fractions in the water, the greater the amount of NOM removed by coagulation. Most of the neutral fraction of NOM is not easily removed by conventional treatment. Generally, alum is the best performing inorganic coagulant for NOM, colour and turbidity removal under conventional pH conditions (6–7) since they are closer to its optimum operating pH range (5–6). On other hand, ferric salts are the best performing inorganic coagulants for enhanced coagulation (higher doses, depressed pH) as these more acidic pH conditions are closer to its optimum operating pH range (4–5).

Poly-aluminium chloride (PACl), also known as aluminium chlorohydrate, is an effective coagulant for low alkalinity waters in situations where pH control cannot be used and acidic coagulants such as aluminium and ferric salts depress the pH below the effective coagulation range. Advanced coagulants (such as poly-ferric sulphate) can remove more DOC over a wider range of operating conditions as they are less dependent on pH and dose.

With respect to SUVA, values of 4 and higher indicate that NOM is dominated by high molecular weight, hydrophobic humic acid fractions and will control the coagulation process with removals greater than 50%. SUVA values in the range of 2–4 indicate that NOM is dominated by a mixture of hydrophobic and hydrophilic fractions of different molecular weights, humic and fulvic acids, as well as other kinds of NOM like algae and algae residues, etc. In such case, DOC removals in the range of 25-50 % can be expected. For raw waters with SUVA below 2, NOM is normally dominated by mostly non-humic, less hydrophobic and low molecular weight substances and it has little influence on coagulation performance. Therefore with SUVA values less than 2, poor DOC removal less than 25% can be expected.

Other common water treatment processes that employ coagulation are sedimentation with filtration, direct filtration, dissolved air flotation with filtration and low pressure membrane filtration. With direct filtration, the flocs formed in the coagulation and flocculation steps are driven directly against media filters and removed through size exclusion. Direct filtration processes have a smaller footprint than conventional or dissolved air flotation processes. Chemical costs are often lower because the required floc size is smaller – resulting in less coagulant use. However, filter runs can be shortened due to fouling, which can lead to increased backwashing.

### 2.3.3. Oxidation processes

Oxidation processes such as ozonation transform NOM into smaller and/or less reactive species that are less likely to form CBPs. Examples of oxidants used in the water treatment industry include ozone, chlorine, potassium permanganate and air (oxygen). Unfortunately, reactions between NOM and certain oxidants (for example, chlorine) can also result in the formation of CBPs such as THMs and haloacetic acids. Studies, including one by Hesse et al. (1999) have shown that large hydrophobic NOM molecules can be converted to smaller and more biodegradable ones through oxidation. Others have also noted that ozonation increases the hydrophilic fraction while decreasing the hydrophobic fractions.

Though ozone on its own is able to oxidize many substances, it can also decompose spontaneously to form other oxidant species such as free hydroxyl radicals. These radicals are highly reactive and non-selective, meaning that they react quickly with most substances in the water. Therefore, total oxidation that occurs when ozone is added to water is partly due to reactions with ozone and partly due to reactions with these hydroxyl radicals. The radicals can be formed through spontaneous ozone decomposition brought about by the addition of hydrogen peroxide or a catalyst or by subjecting hydrogen peroxide to ultraviolet irradiation. Treatment systems based on these reactions have been labelled advanced oxidation processes (AOPs). Speitl et al. (2000) showed that a system using ultraviolet-hydrogen peroxide with biologically active
granular activated carbon (GAC) was nearly as effective at reducing TOC, UV<sub>254</sub>, and disinfection by-product formation potential as a more traditional system using ozone and biologically active GAC. Like all processes, however, there are drawbacks. Most importantly, operating costs can be high, particularly for systems that do not include a post-filtration step that can remove transformed NOM compounds and/or quench residual hydrogen peroxide (Mowat & Hofmann, 2009). This might contribute to the formation of CBPs if precursors are not sufficiently oxidized. In addition, ozone itself is highly corrosive to materials such as wood and rubber. As a result, ozone treatment equipment, piping, and housing must be made of more resistant material such as stainless steel. Such materials tend to be very expensive and ozone residuals in water are short-lived. The gas is also harmful if inhaled. It can therefore present an occupational health and safety risk when used in treatment without taking proper precautions. Elsewhere, advanced oxidation involving hydrogen peroxide and iron-coated pumice have been found effective in removal of NOM (Kitis & Kaplan, 2007; Kaplan Bekaroglu et al., 2010).

2.3.4. Adsorption

Adsorption occurs when one species attaches itself to another through intramolecular forces (that is, dipole interactions, hydrogen bonds, etc). It is mainly used to transfer a chemical species from a liquid or gaseous phase onto a solid one. The solid species is referred to as the adsorbent and the species that is removed from the gas or liquid phase is called the adsorbate. Numerous adsorbents have been developed for use in the water industry. Ion exchange processes work in a similar manner, but rely on both adsorption and the exchange of charged species between the media and the bulk water.

The total amount of adsorbate that can be adsorbed is determined by the media’s adsorption capacity and the time the water spends in contact with it. The latter is referred to as the ‘empty bed contact time’ (EBCT). In general, removal improves with increasing EBCT (Summers et al., 2011). The surface of an adsorbent can be positively or negatively charged and this influences the types of compounds it can remove. Many NOM fractions are charged at ambient conditions and thus can be removed through adsorption. The hydrophobic acid fraction, which is the most extensively studied, is negatively charged at a neutral pH. Consequently, it is most effectively adsorbed when the media is positively charged. Common adsorbents used for NOM removal include activated carbon, ionic resins and metal oxides. Iron coated pumice was also found to be a promising adsorbent (Kitis & Kaplan, 2007; Kaplan Bekaroglu et al., 2010).

2.3.5. Pre-treatment methods

Pre-treatment processes for surface water include application of roughing filters, microstrainers, off-stream storage, oxidants and bank infiltration, each with a particular function and water quality benefit. Pre-treatment may be used to reduce, and/or to stabilise variations in the microbial, NOM and particulate load. Oxidants may be added to water for a variety of purposes including control of taste and odour compounds, removal of iron, manganese and algae among others. Many pre-treatment processes are natural processes enhanced by design to improve water quality. The different options may be compatible with a variety of water treatment processes ranging in complexity from simple disinfection to membrane processes.

Roughing filtration is been mainly applied in the developing world to remove solids from high turbidity source waters prior to treatment with slow sand filters (USEPA, 2003). Elsewhere, however, they have been investigated for removal of other contaminants like iron, algae, etc rather than turbidity (Jayalath, 1994; Reed & Kaprains, 1998; Dome, 2000; Ochieng et al., 2004; Torabian & Fazeli, 2004; Pacini et al., 2005; Dastanaie, 2007; Mukhopadhay et al., 2008; Nkwonta & Ochieng, 2009; Nkwonta et al., 2010). Roughing filters typically consist of a series of compartments filled with progressively reducing size of media particles in the direction of the flow. The media that has been used in such systems include gravel,
plastic, crushed coconut, charcoal, rice husks, or a similar material that is locally available. Roughing filtration systems can either be horizontal or vertical where the later can be up-flow or down-flow. The media in the compartments effectively reduce the vertical settling distance of particles to a distance of a few millimetres and as the sediment builds on the media, it eventually sloughs off and begins to accumulate in the lower section. This process allows regeneration of the upper portions of the filter. Therefore, like any other filters, roughing filters require periodic cleaning to remove the collected sediments. In this study, the performance of a horizontal flow roughing filter with pumice as media was investigated as a pre-treatment unit for the removal of NOM.

3. Application of Indigenous Materials in Water Treatment

3.1. Introduction

Natural materials have been used in water treatment since ancient times but lack of knowledge on the exact nature and mechanism by which they work has hindered their wide spread application. As a result, they have been unable to compete with the commonly used chemicals and other materials like sand, anthracite, activated carbon, etc, that are used as filter media. In recent years there has been a resurgence of interest to use natural materials due to cost and associated health and environmental concerns.

3.2. Natural coagulants

A number of effective coagulants have been identified both of plant and animal origin. Some of the common ones include nimali (Tripathi et al., 1976), M. oleifera (Olsen, 1987; Jahn, 1988), okra (Al-Samawi & Shokrala, 1996), Cactus latijera and Prosopis juliflora (Diaz et al., 1999), tannin from valonia (Özacz & Sengil, 2000), apricot, peach kernel and beans (Jahn, 2001), and maize (Raghuwanshi et al., 2002). Bhole (1995) compared 10 natural coagulants from plant seeds and the study indicated that maize and rice had good coagulation effects when used as primary coagulants or coagulant aid. Chitosan, a natural coagulant of animal origin is also an effective coagulant (Pan et al., 1999; Davikaran & Pillai, 2001; Guibal et al., 2006). It has unique properties among biopolymers especially due to the presence of primary amino groups. It is a high molecular weight polyelectrolyte derived from deacetylated chitin and it has characteristics of both coagulants and flocculants, that is, high cationic charge density, long polymer chains, bridging of aggregates and precipitation (in neutral or alkaline pH conditions). It has also been used for the chelating of metal ions in near-neutral solutions and the complexation of anions in acidic solutions (cationic properties due to amine protonation). Its coagulation and flocculation properties can be used to treat particulate suspensions (organic or inorganic) and also to treat dissolved organic materials. It has also been reported that chitosan possesses antimicrobial properties (Liu et al., 2000; Chung et al., 2003).

Of all the plant materials that have been investigated over the years, the seeds from M. oleifera have been shown to be one of the most effective as a primary coagulant for water treatment. M. oleifera is a small, fast-growing, drought resistant and deciduous tree that ranges in height from 5-12 m with an open, umbrella shaped crown, straight trunk, 10 – 30 cm thick, with corky and whitish bark. The evergreen foliage, depending on the climate, has leaflets 1-2 cm in diameter with white or cream coloured flowers. The fruits or pods are initially light green, slim and tender, eventually becoming dark green, firm and up to 120 cm long, depending on the variety. Fully mature dried seeds are round or triangular in shape, the kernel being surrounded by a lightly wooded shell with three papery wings. It can be easily propagated by cutting or by seed. In a favourable environment an individual tree can yield 50 to 70 kg of pods in one year (Schwarz, 2000). Since the early 1970’s a number of studies have been carried out to determine the effectiveness of the seeds for the treatment of surface water (Olsen, 1987; Jahn, 1988; Sutherland et al., 1994; Muyibi &
Evison, 1995 & 1996; Ndabigengesere & Narasiah, 1998; Okuda et al., 2001a & b; Ghebremichael, 2004) using different extraction methods for the active coagulant. Utilising artificially prepared turbid water and naturally turbid raw waters, laboratory investigations have confirmed the seeds to be highly effective in the removal of suspended solids from waters containing medium to high initial turbidities (Sutherland et al., 1994). Pilot and full-scale plant trials carried out in Malawi at Thyolo Water Treatment Works demonstrated that the seeds could be used effectively on continuous flow systems producing treated water quality similar to that of aluminium sulphate (Folkard et al., 1995). In their research, Jahn (1979) investigated the potential of the plant seeds and roots on removal of turbidity and compared it with alum. He extracted the coagulating agent from seed powder and roots using water and observed that in terms of turbidity removal, the crude seed suspension compared well with that achieved with alum. Due to the drawbacks of extracting the active coagulant from M. oleifera using water, researchers such as Ndabigengesere et al. (1995) and Okuda et al. (1999 & 2001a) went ahead to purify and characterise active coagulating agent from M. oleifera seeds using other methods. Ndabigengesere et al. (1995) used ammonium precipitation, dialysis, ultra-filtration, sodium dodecyl sulphate – poly acryl amide gel electrophoresis, ion exchange chromatography and polyacryl amide gel iso-electric in the extraction and purification of the active components (proteins). He finally used lyophilisation technique to concentrate the purified proteins. They observed that the active agent was a water-soluble cationic protein that harbours very good coagulation properties requiring extremely lower dosages than used for crude seed extract. However, the extraction and purification methods involved seem to be mainly for experimental purposes and are most likely difficult to be scaled up for its ultimate use in water treatment facilities in poor countries. Okuda et al. (1999 & 2001a) extracted M. oleifera coagulant using 1M sodium chloride solution and the extracted coagulant (MOC-SC) showed better coagulation activity with dosage 7.4 times lower than that of coagulant extracted with distilled water. The improvement in coagulation activity was attributed to the salting-in mechanism of sodium chloride on proteins present in the seed powder suspension. Ghebremichael (2004) working with M. oleifera came up with a simple, rapid method of extraction and purification of the coagulating proteins that would be scaled-up to full-scale plant application. In this study, investigations on the performance of MOC-SC as both a primary coagulant and coagulant aid in treatment of swamp water were carried out (Paper VI).

By using natural coagulants, considerable savings in chemicals and sludge handling cost may be achieved. Al-Samawi and Shokrala (1996) reported that 50 – 90% of alum requirement could be saved when okra was used as a primary coagulant or coagulant aid. Apart from being less expensive, natural coagulants produce readily biodegradable and less voluminous sludge. For example, sludge produced from M. oleifera coagulated turbid water is only 20 – 30% of that generated when aluminium sulphate is used (Ndabigengesere et al., 1995; Narasiah et al., 2002).

### 3.3. Filtration/ adsorption media

The coagulation process in water treatment is complimented by filtration. The successfulness of coagulation in most cases determines the performance of the filtration system, which may be of a mono medium or dual media type. Some of the indigenous materials that have been used in single or multimedia filtration systems include crushed coconut shells, burned rice husk (Frankel, 1974), human air (Wasiuuddin et al., 2002), crushed apricot shell (Aksogan et al., 2003), pumice (Ghebremichael, 2004), palm leaves and shrimp shells (Aly et al., 2005). Paramasivan et al. (1973) reported that high-grade bituminous coal used in dual media filtration could be a good substitute for anthracite coal. In his study, Ghebremichael (2004) showed that pumice obtained from Eritrea would be used as a dual filter media to give longer filter runs than obtainable in a single medium (sand).
filter. In addition to these materials, another material that has not received much attention and would probably be used for water treatment is volcanic ash.

Volcanic ash and pumice are formed during explosive volcanic eruptions. Volcanic ash consists of very fine rock and mineral particles less than 2 mm in diameter ejected from a volcanic vent (Fig. 3 and 4). Ash is created when solid rock shatters and magma separates into minute particles during explosive volcanic activity. The usually violent nature of an eruption, involving steam (phreatic eruption) results in the magma and perhaps solid rock surrounding the vent being torn into particles of clay to sand size. Unlike the soft and fluffy ash that forms from burning wood or other combustible materials, volcanic ash is hard and abrasive. It does not dissolve in water, and it conducts electricity, especially when it is wet. The volcanic ash deposits lie on the surface so it is easy to mine. It has varying colours ranging from black, grey, brown and yellow. The specific gravity of volcanic ash obtained from south-western Uganda was in the range of 2 to 2.5 (DGSM/DCE-UT, 1992). Other materials similar to volcanic ash do have identical values: pumice - 1.96, shale - 2.58, diatomite - 2.65, limestone - 2.69, tile - 2.59 (Perry & Chilton, 1973). In Uganda, volcanic ash has been employed as aggregate in production of lightweight blocks, in sewage sludge drying bed and in the production of cement. In this study, the performance of the volcanic ash in dual media filtration of drinking water was investigated (Paper III).

Pumice is also created when super-heated, highly pressurized rock is violently ejected from a volcano. It results from simultaneous actions of rapid cooling and rapid depressurization when lava and water are mixed. Pumice is commonly pale in colour, ranging from white, cream, blue or grey, to green-brown or black (Fig. 5). It is widely used as an abrasive in polishes, erasers and cosmetic exfoliates. It is also used in the making of lightweight concrete or insulative low-density blocks and as a growing substrate for horticultural crops because of its capacity to hold moisture for longer periods than normal soil. For water treatment, it has been researched on as an adsorbent and catalytic media in oxidation of NOM (Kitis et al., 2005; Kitis et al., 2007). It has also been used as media in rapid filtration units (Farizoglu et al., 2003). In this study, pumice was

Fig. 3. Deposit of volcanic ash in south western Uganda.

Fig. 4. SEM for volcanic ash from south western Uganda.

Fig. 5. Mixture of grey and red pumice obtained from south-western Uganda.
investigated as media in a roughing filter and as catalytic media in oxidation of NOM with hydrogen peroxide (Paper IV & V).

4. MATERIALS AND METHODS

4.1. Water Treatment Plants

4.1.1. Kampala waterworks (Ggaba II plant)
At Kampala waterworks like elsewhere in the country, conventional methods are used for treatment of water. At Ggaba II plant, water treatment train includes the clarification (coagulation, flocculation and sedimentation), rapid sand filtration and disinfection unit processes. The plant draws its raw water from the Inner Murchison Bay of Lake Victoria, a freshwater lake. The different treatment stages were assessed on the basis of design criteria, treatment effectiveness, operation and maintenance procedures (Paper I). The assessment was based on one-year (2005) data. Samples were taken at locations 1, 2, 3 and 4 (Fig. 6) for raw, clarified, filtered and final treated water, respectively. The service water samples were taken from the backwash tank. Additional information related to the raw water source, the plant operation and design was obtained from NWSC staff. The water quality parameters measured were pH, colour, turbidity, DOC, TOC, free chlorine and total chlorine (Paper I).

4.1.2. Masaka waterworks (Boma plant)
The water treatment works extract raw water from River Nabajjuzi swamp dominated by Cyperus papyrus, L., which water contains relatively high levels of both NOM and iron. The treatment processes run from pre-chlorination/aeration, clarification (coagulation, flocculation and sedimentation), filtration and disinfection. The pre-chlorination stage is applied for the oxidation of iron. The study was carried out at Boma water treatment plant (BWTP) whose schematic layout is presented in Figure 7. Raw water and the treated water from each process were sampled once a day per week for one year. Characterization of NOM in treated water from the unit processes was done with two samples taken during the dry season while one was taken during the wet season. Other parameters analyzed included DOC, pH, conductivity, colour, turbidity and total iron (Paper II).

4.2. Characterisation of Materials used in the Study

4.2.1. Preparation of volcanic ash, pumice and M. oleifera
The volcanic ash was obtained from deposits along Kabale – Kisoro road in south-western Uganda, crushed, sieved and graded to the size suitable for filtration while the sand was sampled from that used at Ggaba II treatment plant filters (Paper III). Both the sand and volcanic ash were sieved to an effective size of 1 mm. Sieve analysis was carried out in accordance with procedures laid down in BS 1377 (British Standard Institution, 1990).

The pumice used in the study was also obtained from deposits in Kisoro, south-western Uganda. There were two kinds of pumice collected, the red and grey coloured. These were both used without segregation. For the HRF, pumice was crushed to size ranges of 40 to 35, 35 to 20 and 20 to 15 mm and washed with tap water before use. For the measurement of specific surface area, the red and grey pumice were crushed to four fractions using a set of sieves yielding particles with diameters between 1–2, 0.5–1, 0.25–0.5 and 0.125–0.250 mm. The size fractions were washed using de-ionized water to remove fine rock dust that had not been separated during sieving before measurements for surface area were done.

For the batch adsorption and catalytic oxidation experiments, both the original pumice (OP) and pumice obtained from the roughing filter (HRFP-P) were crushed and sieved to an effective size of 1 mm (Paper V). It was thereafter soaked in hydrochloric acid solution at pH 1 for 24 hours at room temperature after which it was rinsed with distilled water several times before drying in an oven at 105°C for 24 hours (Paper V). Rinsing was done until a clear supernatant was obtained with total iron and turbidity less than 0.1 mg/l and 1 NTU, respectively. The HRFP-P used in the laboratory scale HRF
received no pre-treatment except washing it with tap water followed by distilled water.

The material properties tested for volcanic ash were specific gravity, acid solubility and hardness (Paper III) while for pumice, material characteristics analyzed were specific surface area, mineral composition, morphology, zeta potential, acidity, basicity, pH at point of zero charge and density (Paper IV).

The *M. oleifera* seeds (Paper VI) were obtained from the Faculty of Veterinary medicine, Makerere University. The seeds were stored in dry conditions at room temperature (24 ± 1°C). Only seeds of dry pods were used. The winged seed cover was removed just before crushing and extraction process for the active coagulant with 1N sodium chloride solution. The kernel was ground to a fine powder by using a kitchen blender. Oil was removed by mixing the powder in 95% ethanol (5 -10% w/v) for 30 minutes. The solids were separated by centrifugation and dried at room temperature for a period of 24 hours. From the dried sample, 5.0 g of the seed powder was mixed with 500 ml of the extractant (1 N NaCl). The suspensions were stirred for 30 minutes using a magnetic stirrer and filtered first through Whatman No. 3 then through fibreglass filter and finally through 0.45 μm filter. The filtrate (MOC-SC) was used for coagulation experiments either immediately or within 3 days of storage at room temperature. Alum (17% Al₂O₃) used in the study was obtained from Kampala water treatment works.

4.2.2. Specific surface area

BET-measurements were carried out using an ASAP 2000 Micromeritics with nitrogen as the analysis gas (Paper V). The surface areas were determined using four measurements in the relative pressure range 0.05–0.30. Equation (3) adopted from André *et al.* (2008) was used to obtained extrapolated specific surface areas of particle sizes used in the HRF from measurements of crushed pumice.

\[
A_{\text{spec}} = \frac{6\lambda}{L\rho} + A_{\text{int,spec}}
\]

Where \(A_{\text{spec}}\) is the specific surface area, \(A_{\text{int,spec}}\) is the internal specific surface area and extrapolated value for the specific surface area of the intact rock sample, \(L\) is the length of the cube sides and \(\rho\) is the sample density. The length \(L\) of the cube sides was taken as

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**Fig. 6. Ggaba II water treatment plant process units**
4.2.3. Mineral composition, morphology, specific gravity and porosity

Loss on ignition of volcanic ash was determined by ignition at Analytical Laboratory, Malmö in Sweden while the mineral composition and morphology of the pumice were determined by X-ray diffraction (XRD) and SEM/SEM-EDS, respectively. The specific gravity was determined according to the pyconometer method in BS 1377 (British Standard Institution, 1990) while the acid solubility of volcanic ash was determined following American water works association standards for filtering materials (AWWA, 1998). The material strength was determined by scratching the material with different minerals in Mohr’s scale.

4.2.4. Acidity and basicity

The concentration of total acidic and basic groups (total acidity and basicity) on pumice surfaces was determined from uptake sodium hydroxide (NaOH) and hydrochloric acid (HCl), respectively (Paper IV). Several 25 ml vials, each with 100 mg of pumice sample, were prepared and filled with 20 ml of 0.05 N NaOH or 0.05 N HCl. Vials without pumice were also prepared and served as blanks. Samples and blanks were shaken at 200 rpm for 48 hours at room temperature, and then left to stand for 6 hours to allow pumice particles to settle. 10 ml of the solution from each vial was titrated with 0.05 M of either NaOH or HCl solution. The difference between NaOH or HCl consumption by the blank and samples was calculated and translated to the equivalent acidity or basicity per gram of pumice.

4.2.5. Zeta potential and pH at point of zero charge

Zeta potential (ZP) measurements were carried out with a Malvern ZS90 Zetasizer using He–Ne red laser beam (λ: 633 nm) through M3-PALS (Mixed Mode Measurement Phage Analysis Light Scattering) technique. Pumice powders were dried in an oven at 110°C for 2 hours and stored in a plastic bag prior to measurements. 2 g of pumice powder was dispersed into 50 ml of a background electrolyte solution of 1 mM NaCl to ensure a constant ionic strength. The pH at point of zero charge (pH_{PZC}) was determined as the pH of the NaCl solution that did not change after contact with the samples. One-tenth molar of sodium chloride (NaCl) solutions having different pH values (2–11) were prepared using deionised water that was boiled for removal of dissolved CO₂. Solutions of 0.5 N HCl or NaOH were used in pH adjustment. 100 mg of pumice samples were contacted with 20 ml of 0.1 M NaCl solutions with different initial pH values in 25 ml vials. Blanks with no pumice were also run with the samples. Duplicate experiments were performed for all samples. Sealed vials were shaken for 48 hours at 200 rpm at the room temperature, and then left to stand to

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Fig. 7. Schematic layout of the unit treatment processes at Masaka (Boma) water treatment plant.
allow settling of the pumice particles. The final pH of the solution was measured.

4.3. Experimental Strategy

4.3.1. Laboratory scale experiments

Batch adsorption experiments

Adsorption experiments were performed in bed of filter in a 2 l-square jar with samples (50 ml) taken off from the bottom of the jar at periods of 0.5, 1, 2, 4, 8, 24, 48 and 96 hours for the analysis of DOC and total iron. The experiment was carried out in a laboratory with normal lighting with the top of the jar sealed using an aluminium foil. Variable hydrogen peroxide dose experiments were carried out in conical flasks of 250 ml volume for both the crushed OP and HRFP-P. After a period of 24 hours, the water was decanted off and filtered through a 0.45 μm filter membrane and analysed for DOC to assess NOM removal. All experiments were conducted at natural pH values between 5.5 and 7.0.

Laboratory-scale horizontal roughing filter

This consisted of a raw water tank, two peristaltic pumps and two circular troughs each 1.6 m long cut from 200 mm-diameter perspex pipes (Fig. 8). One unit contained pumice obtained from the existing pilot scale roughing filter (HRFP-P) and second unit did not contain any filter media (the Control). The pumice was arranged in sections along the trough with the first 0.6 m containing media of 40 to 35 mm diameter, followed by media with 35 to 20 mm diameter then 20 to 15 mm diameter each occupying 0.5 m length. The units were operated for a period of six months at retention time of 24 hours.

Analytical grade hydrogen peroxide was used in the study at concentration of 300 mg/l. The tank dosed with the peroxide was sealed to lessen the interference of natural light before the water entered the filters. Raw water used in the experiment was collected from River Nabajjuzi.

Jar test

Jar tests were carried out to assess the impact of pre-treatment using the HRF on the subsequent coagulation process and THMs formation on post chlorination (Paper IV); and the coagulation activity of MOC-SC both as a primary coagulant and as coagulant aid (Paper VI). The standard procedure for the jar test was followed. Each beaker of the ECE Compact Laboratory Mixer was filled with 1000 ml of the sample to be coagulated. Immediately after dosing, rapid mixing was done at 150 rpm for 1 minute. Thereafter, the speed was reduced to 30 rpm to allow gentle mixing for 30 minutes. After sedimentation for 1 hour, 100 ml-portions were sampled from the mid depth of each beaker for further analysis.

For jar tests with MOC-SC (Paper VI), alum doses ranging from 0 to 110 mg/l were applied while doses of MOC-SC ranged from 0 to 270 mg/l. To assess its performance as a coagulant aid, 100 mg/l of MOC-SC was added at the start of gentle mixing period to each of the jars dosed with 0 to 110 mg/l alum. Residual turbidity, colour, electrical conductivity, pH, DOC and ferrous iron were determined. The concentration of MOC-SC is stated in mg/l on the assumption that all the MOC dissolved. Tests with the HRF filtrate, raw water and pre-chlorinated water were carried using alum doses ranging from 0 to 50 mg/l (Paper IV).

In all the tests, a 1% solution of alum in distilled tap water was used. The alum

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**Fig. 8. Schematic diagram of the laboratory-scale horizontal roughing filter.**
powder was totally soluble in the water. Experiments were conducted at room temperature (25 ± 1 °C) and circum-neutral pH values (5.5 – 6.9). pH adjustment was done only for pre-chlorinated water (Paper IV). A dosage of 10 mg/l of calcium hypochlorite was used to assess the trihalomethanes formation potential (THMFP) of the pre-treated water and coagulated water (Paper IV).

4.3.2. Pilot plant experiment

Volcanic ash columns-Kampala waterworks (Paper III)

The study was carried out using filtration columns set up adjacent to Ggaba II water treatment plant (Paper III). Six columns of high-density polyethylene pipes 1.5 m high with a 150-mm internal diameter were used. Support gravel was provided at the bottom of each column to retain the granular filter media. To ensure uniform filtrate collection and backwashing, nozzles were provided at the bottom of 10 cm-deep graded gravel bed. Raw water was pumped from the intake of the plant and supplied to the columns from a feed-tank by gravity to control the loading rate.

Horizontal roughing filter

The installation consisted of a raw water intake unit (pump), an overhead tank and a HRF unit composed of three compartments: the first compartment 1.8 m long containing media of 40 to 35 mm diameter, second compartment 1.5 m long for media with 35 to 20 mm diameter, and the third compartment with a 1.5 m length for media with 20 to 15 mm diameter (Fig. 9). Large sizes were used to ease the cleaning of the bed. Chambers with 200-mm lengths were installed at the inlet, in between chambers and outlet of filter box for onsite measurements and sampling. The effective height of filter media and maximum water level were 750 and 600 mm, respectively. Gate valves, each 50 mm in diameter, were fixed at the bottom of the filter box to allow removal of accumulated sludge and increase the washing efficiency (Fig. 9 and 10). A gate valve was installed at the inlet to adjust and control the loading rate. Raw water was pumped to an overhead tank (100 litres) from where it was flowing by gravity to the HRF. The unit was operated for 2 ½ years.

4.4. Analytical Procedures for Water Quality Testing

4.4.1. Parameters and techniques investigated

A summary of parameters measured and techniques used are presented in Table 4 and 5. Samples for total iron were collected in glass bottles and preserved using 0.5 ml of nitric acid. Samples for analysis of THMs were collected in 500-ml glass bottles with solid ground glass stoppers. The bottles and stoppers were baked in an oven for 3 hours at 105°C ± 5°C and allowed to cool to room temperature. A small amount (spatula full) of sodium thiosulphate was added in each bottle to react with the chlorine present in the water, and thereby prevent further THM formation. Sample bottles were filled and

| Table 3: Parameters of filter media used in the study. |
|---------------------------------|-----------------|-----------------|--------|-----------------|-----------------|--------|
| Sand                            | Volcanic ash    |
| Effective Size (mm)             | Uniformity Coefficient | Depth (cm) | Effective Size (mm) | Uniformity Coefficient | Depth (cm) |
| Sand column                     | 0.65            | 1.71            | 60        | 1.10            | 1.20            | 45     |
| Ash-sand column                 | 0.50            | 1.30            | 15        |                 |                 |        |

Removal of natural organic matter and trihalomethanes formation control in water treatment
sealed carefully so that no air bubbles were entrapped. The samples were stored in a refrigerator and on the next day sent to Umgeni water laboratory for the analysis of THM (Paper VI). No preservative were added to these bottles. For experiments done from Makerere University and NWSC laboratories, samples were analysed immediately on collection. Samples for the analysis of bulk TOC and DOC were collected in 1-litre amber-coloured glass bottles.
4.4.2. NOM fractionation

Samples were collected in 40-ml glass vials covered with Teflon-lined septa caps, filled so that no air was trapped within the sample and sealed tightly. The samples were kept at 4°C and transported to the laboratory. Characterization into different fractions was performed with a size exclusion chromatography (LC-OCD) system (DOC-LABOR, Germany) (Paper II). Fractional composition was determined by integration of the area under each chromatogram using FIFFIKUS (DOC-LABOR) software.

4.4.3. Algae

Quantification of algae was done at the Department of Zoology, Makerere University, Kampala. An aliquot of 10 ml from each of the column influent and filtrate samples was fixed with Lugol’s solution, sub-sampled into a 2 ml sedimentation chamber and counted after 12 hours of sedimentation under an inverted microscope (Hund Wetzlar: magnification x 200). Different identification keys were used to identify the algae genera. For filter media, each sample of media was washed with distilled water to remove any organisms from the surface and the supernatant was quantitatively analyzed through sub-sampling. The flora was fixed with Lugol’s solution, sub-sampled into a 2 ml sedimentation chamber and counted under an inverted microscope after 12 hours of sedimentation.

4.4.4. Taste of treated water:

To determine the impact of MOC-SC on the taste of treated water, ten individuals were given portion of the settled, filtered and chlorinated water (Paper VI). They were chosen in such a way that they were unknown to one another to avoid biases. During the experiment, the source of the water was not declared to them. Comparison

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### Table 4: Summary of parameters measured in papers I to VI.

<table>
<thead>
<tr>
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<td>✔</td>
<td>✔</td>
<td>✔</td>
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<tr>
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<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
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</tr>
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<td>✔</td>
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</tr>
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<td>✔</td>
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<tr>
<td>Algae</td>
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<td>✔</td>
<td>✔</td>
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<tr>
<td>Head loss</td>
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<tr>
<td>Residual chlorine</td>
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<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
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</tr>
</tbody>
</table>

### Table 5: Summary of methods used to measure parameters in papers I to VI.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Method</th>
<th>Parameter</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colour</td>
<td>Hach DR 4000 spectrophotometer (Paper I &amp; II); Hach DR2010 Spectrophotometer (Paper III); Hach DR 2000 Spectrophotometer (Paper IV &amp; VI)</td>
<td>Iron</td>
<td>DR 2000 Hach Ferrozine method 260 (Paper IV &amp; VI); Atomic absorption spectrometer Perkin Elmer 2380 (Paper II, IV &amp; V).</td>
</tr>
<tr>
<td>Turbidity</td>
<td>Hach DR 2000 Spectrophotometer (Paper VI); DR 4000 spectrophotometer (Paper I &amp; II)</td>
<td>DOC/TOC</td>
<td>Shimadzu V&lt;sub&gt;CON&lt;/sub&gt; TOC – analyser (Paper IV &amp; V) Shimadzu TOC 5000A analyser (Paper I &amp; VI)</td>
</tr>
<tr>
<td>Conductivity</td>
<td>Hach portable meter (Paper I) Orion portable meter (Paper II) WTW Cond 330i meter (Paper VI)</td>
<td>THM</td>
<td>Gas chromatography (GC) with an Electron Capture Detection (ECD) (Paper II &amp; VI); DR/2010 Spectrophotometer - THM Plus™ method (Paper II &amp; IV).</td>
</tr>
<tr>
<td>pH</td>
<td>Hach sensION1 meter (Paper I &amp; VI) Orion portable meter (Paper II, IV &amp; V)</td>
<td>UVA</td>
<td>Shimadzu UV-VIS 1601 spectrophotometer (Paper II)</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>HACH 2010 Spectrophotometer (Paper II &amp; III)</td>
<td>Residual chlorine</td>
<td>Hach DPD calorimetric method (Paper I)</td>
</tr>
</tbody>
</table>
was made to tap water from the drinking water mains.

4.5. Quality Control

Samples for iron were analysed in triplicates and the average taken for every sampling routine. Ferrous iron was analysed in the field laboratory immediately to prevent it from being oxidised to ferric iron while samples for total iron were preserved using 5 N nitric acid. All glassware was rinsed with a 1:1 hydrochloric acid solution and finally with deionised water. For spectrophotometer measurements, blank sample readings were checked every after 5 samples where a non-zero for the blank indicated need for cell cleaning, or variations in the spectrophotometer response caused by heating since it was being used over a long time. For TOC or DOC measurements, there will be a positive error if the TOC of the reagent water is significant compared to the TOC of the sample. To avoid this, carbon-free reagent water was used. Only glassware cleaned with chromic acid was used.

5. RESULTS AND DISCUSSION

This chapter focuses on the results obtained in the different experiments performed to accomplish the objective of effective removal of NOM and control the formation of THMs in water treatment using indigenous materials. An assessment of water treatment plants (Ggaba II and Boma) is presented. After the assessment of plants, emphasis was directed to Masaka water source where the performance of the horizontal roughing filter was investigated in the removal of NOM and iron.

5.1. Assessment of Drinking Water Treatment Processes

Ggaba plant abstracts raw water from Lake Victoria, a fresh water lake and Boma plant in Masaka abstracts its raw water from River Nabajjuzi swamp. The water treatment trains at the plants constitute similar unit processes, that is, pre-chlorination, clarification, rapid sand filtration and disinfection despite the fact that they have sources of different water quality characteristics. At Ggaba II plant, the pre-chlorination process was introduced later to oxidize algae whereas in Masaka, it is mainly intended for oxidation of iron.

5.1.1. Kampala waterworks (Ggaba II plant)

At Ggaba II plant; raw water flows by gravity to the raw water sump from where it is pumped to the alum dosing chamber for rapid mixing with coagulant by a hydraulic jump. Thereafter, it again flows by gravity to the subsequent treatment units. Data collected and analysed indicated a significant change (at 5% confidence level) in the quality of raw water with an increase in colour (Fig. 11) of about two fold in the period 1997 to 2005 (Paper I). From 2001 to 2005, the colour increased with reducing rainfall. The annual mean colour values of 198, 158 and 154 PtCo were recorded for 2009, 2010 and 2011, respectively (NWSC, 2012). These colour values are higher than those recorded in 2005 but with a reducing trend. The change in quality would probably be attributed to a combination of factors including dilution, storm water runoff during the wet periods and concentration effects during dry periods. Warmer temperatures can increase organic content and nutrient cycling within a water body. This change in the raw water quality is expected to impact on the overall performance of the plant. With a high colour, the risk is high for the production of by-products during the disinfection processes (WHO, 2011). A summary of results from the assessment of the performance of the plant is given in Table 6. Results indicated that clarification was a significant factor (p-value = 0) in determining the performance of the subsequent treatment processes. Reduction in TOC and DOC of 64% and 46%, respectively, were achieved after clarification. The raw water had TOC and DOC content of 7.1 and 4.7 mg/l, respectively. The filters did not contribute to the removal of organic matter as indicated by the increases in TOC and DOC of 28% and 8%, respectively in the filtrate. The increase in organic matter would probably be explained by the presence of algae in the filters. A rapid drop of the residual chlorine concentration (to less than 0.5 mg/l) within the water treatment plant premises (Paper I) could also be explained by organic carbon
In addition to the deteriorating raw water quality, there were also design, operation and maintenance shortcomings of the clarification and filtration units (Paper I). Regarding the clarification unit, the desludging hoppers are located on one side of the clarifiers resulting in inadequate sludge blanket removal and carryover of flocs to the filters. The unequal distribution of water to the different units, the shrimps and algae in the units also probably contributed to the break-up of the sludge blanket thus carryover to the filters. Bypassing the clarifiers also resulted in overloading of the filters and proliferation of algae thus resulting in production of inadequately treated water. However, with the clarifiers in operation, algae would still be carried over to the filters because high population of algae and plankton are difficult to coagulate and usually float (Quasim et al., 2000). During periods of high algal bloom the blanket had a tendency of becoming buoyant due to production of oxygen during times of high algal blooms. This could also have resulted in a billowing of the floe blanket and subsequent carry-over of flocs and algal cells to the filters. As result, the filtration run lengths were shortened and a lot of water had to be used during back-washing. However, with the introduction of the pre-chlorination stage for the oxidation of algae, the final water quality with respect to colour, turbidity and pH greatly improved. Annual means of colour and turbidity less than 5 PtCo and 1 NTU, respectively, have been recorded since 2009. But there is need to assess the final water with respect to algal toxins and chlorination by-production that might arise from the pre-chlorination stage.

**Table 6: Final water quality at Ggaba II water treatment plant for year 2005 (Paper I).**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean (SD)</th>
<th>Compliance (%)</th>
</tr>
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<tbody>
<tr>
<td>pH</td>
<td>6.65 (± 0.29)</td>
<td>21.6</td>
</tr>
<tr>
<td>Colour (PtCo)</td>
<td>32 (± 34)</td>
<td>53.4</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>2.4 (± 2.1)</td>
<td>9.3</td>
</tr>
<tr>
<td>Conductivity (µS/cm)</td>
<td>145 (± 20)</td>
<td></td>
</tr>
<tr>
<td>Free chlorine (mg/L)</td>
<td>1.11 (± 0.30)</td>
<td></td>
</tr>
<tr>
<td>Total chlorine (mg/L)</td>
<td>1.29 (± 0.33)</td>
<td></td>
</tr>
</tbody>
</table>
5.1.2. Masaka waterworks (Boma plant)

Like Ggaba II plant, raw water is pumped to the pre-chlorination/aeration units from where it subsequently flows by gravity to the rest of the treatment units. It abstracts raw water from River Nabajjuzi swamp known to contain relatively high levels of humic materials. Therefore, it was important to understand the character of NOM in this water source if appropriate treatment unit processes are to be designed for its removal. Characterization of NOM indicated that 79% of the TOC was in the dissolved form (DOC) with 83% of the DOC being hydrophilic. The hydrophilic component was mainly composed of biopolymers (MW >=20,000 g/mole) with low dissolved organic nitrogen (DON), humic substances (approx. 1000 g/mole), building blocks (300 – 500 g/mole) and low molecular weight neutral compounds (< 350 g/mole) (Paper II). All the fractions, apart from the biopolymers, were poorly removed along the treatment train. In some natural water sources, the hydrophobic fraction, which is much easier to remove by conventional treatment, has been reported to be the major component while in others the hydrophilic fraction dominates (Liang & Singer, 2003). Lim et al. (2009) found the hydrophobic acids (40%) to be the most dominant followed by hydrophilic neutrals (22%) in Semenyih River, Malaysia. Elsewhere hydrophobic acids were reported to make up approximately 50% of the DOC (Thurman, 1985; Owen et al., 1993). This indicates how NOM characteristics can vary from one location to another.

Characterization results along the treatment train indicated no variation in the NOM character (Fig. 12). From the chromatograms, there was a reduction in the high molecular UV absorbing fraction of NOM while more building blocks were formed. When humic substances are oxidised, building blocks may be formed that cannot easily be removed by flocculation (Abert, 2008). This is further indicated by the poor removal of the same fraction in the subsequent processes. To understand further the reactivity of NOM with chlorine, SUVA was determined at the different stages of water treatment within the plant. Related to the organic carbon, SUVA of given water can give a good indication of its reactivity against chlorine (Frimmel, 2000). SUVA values were determined at 280 nm (SUVA<sub>280</sub>) to minimize the interference by iron given that the raw water had an average total iron concentration of 5.09 mg/l. Values varied from 2.27 l/mg-m for raw water to 0.771/mg-m for final water (Paper II). Natural waters with SUVA values ≥4 L/mg-m are reported to have a relatively high content of hydrophobic, aromatic, and high molecular weight NOM fractions, whereas waters with values ≤ 3.1/mg-m contain largely non-humic, hydrophilic and low molecular weight materials (Świetlik & Sikorska, 2005). The results indicated further the hydrophilic nature of NOM and implied that water from the various stages of the treatment still had a potential of reacting with chlorine to form CBPs. In their study, Rostad et al. (2000) reported SUVA of five water fulvic acids, the most similar to the hydrophilic acids isolated, to range from 2.86 to 4.28 l/mg-m, whereas values of surface water humic acids, the most similar to colloids isolated to range from 4.86 to 7.36 l/mg-m. Whilst the relative reactivity of the hydrophobic fraction is typically higher than of the hydrophilic fraction, there are a number of examples where this relationship does not always fit. With minimal hydrophobic fraction, the major contributor to THM formation in this case was the hydrophilic fraction. Elsewhere, Owen et al. (1993) showed that hydrophilic material is the main cause for concern with regards to its THM formation potential (THMFP). It was reported that 65% of the TOC and 56% of the THMFP from the Colorado river was contributed by hydrophilic compounds and that these were exerting the largest chlorine demand when compared to the hydrophobic material (2.4 mg Cl₂/ mg hydrophilic vs. 0.32 mg Cl₂/ mg hydrophobic), which consequently meant a higher concentration of THMs. Similar studies on assessment of water treatment plants carried out elsewhere are presented in Table 7.
5.2. Use of Volcanic Ash in the Pre-filtration of Algal-laden Water

5.2.1. Head loss development

Cost effectiveness in filtration systems means that filter run lengths between filter-cleanings are long enough to offset the cost of filter down times and increasing filter backwash volumes. In most cases, filter run length is based on turbidity; however, raw water turbidity alone may not be an adequate predictor of filter-run length (Cleasby et al., 1984). In addition to turbidity, quantification of raw water algal content is essential for judging the acceptability of the raw water into the filters. This is especially important for eutrophic water because the algal bloom greatly affects the performance of the treatment plant (Rositano et al., 2001; Hiroshi et al., 2002) and the quality of the final water.

In this study, an increase in filter run length of about two and half folds that of the mono media (sand) was observed in the dual-media (volcanic ash/sand) filter (Paper III). This is a basic advantage of dual media over mono-medium filtration systems, where only the top few centimetres of layer of the medium is utilised. Ghebremichael (2004) made a similar observation with pumice as dual medium. At the 35th hour, the mono medium and dual media filters had reached a head loss of 65 and 40 cm, respectively (Fig. 13). This increase in the filtration run length of the
The dual media filter may be attributed to the characteristics of the volcanic ash providing more storage capacity for the suspended particles than the sand. This is indicated by the insignificant difference in the water quality after the ash in the dual media filter and filtrates of both filters. The head loss in either filters was significantly affected by the raw water colour ($p = 0.02 < 0.05$), the type of media arrangement ($p = 0.00 < 0.05$) and loading rates ($p = 0.00 < 0.05$). Part of the colour was visibly due to the presence of algae in the raw water.

### 5.2.2. Algae proliferation

During the study, algae appeared to be the major challenge affecting the filtration and clarification processes at Ggaba II treatment plant (Paper I). Six genera of cyanobacteria (*Anabaena*, *Aphanthece*, *Coelospherium*, *Merismopedia*, *Microcystis* and *Oscillatoria*) and eight genera of chlorophyceae (* Ankistrodesmus*, *Closterium*, *Cystodinium*, *Pediastrum*, *Scenedesmus*, *Selenastrum*, *Spirulina* and *Staurastrum*) were identified in the raw water. *Spirula* ($2.5 \times 10^4$ cells/ml) and *Anabaena* ($2.9 \times 10^4$ cells/ml) were the most dominant

### Table 7: Similar studies that have been carried out at various water treatment plants.

<table>
<thead>
<tr>
<th>Location</th>
<th>Plant</th>
<th>Processes</th>
<th>Characterisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thailand</td>
<td>Takua Pa</td>
<td>Coagulation, sedimentation tank, filtration &amp; free chlorination</td>
<td>TOC, THMs &amp; Algae (Collivignarelli et al., 2008)</td>
</tr>
<tr>
<td>South Africa</td>
<td>Vaalkop</td>
<td>EC, ozonation, granular activated carbon &amp; chloramination</td>
<td>Hydrophobic &amp; Hydrophilic fractions using XAD resins (Nkambule, 2009) DOC (Haarhoff et al., 2010)</td>
</tr>
<tr>
<td>Vereeniging</td>
<td>EC, sedimentation &amp; chloramination</td>
<td>DOC (Haarhoff et al., 2010)</td>
<td></td>
</tr>
<tr>
<td>Balkfontein</td>
<td>EC, sedimentation, rapid sand filtration &amp; free chlorination</td>
<td>DOC (Haarhoff et al., 2010)</td>
<td></td>
</tr>
<tr>
<td>Stillfontein</td>
<td>dissolved air flotation, sedimentation, ozonation, rapid sand filtration &amp; free chlorination</td>
<td>DOC (Haarhoff et al., 2010)</td>
<td></td>
</tr>
<tr>
<td>Namibia</td>
<td>Von Bach</td>
<td>Sedimentation, rapid sand filtration &amp; free chlorination</td>
<td>DOC (Haarhoff et al., 2010)</td>
</tr>
<tr>
<td>Goreangab</td>
<td>Pre-ozonation, EC, dissolved air flotation, rapid sand filtration, ozonation, biological activated carbon, granular activated carbon, ultra filtration &amp; free chlorination</td>
<td>DOC, BDOC &amp; NBDOC, Molecular weight distribution using HLSEC technique (Haarhoff et al., 2010)</td>
<td></td>
</tr>
<tr>
<td>Uganda</td>
<td>Boma (Masaka)</td>
<td>Pre-chlorination, coagulation, sedimentation, filtration &amp; chlorination</td>
<td>TOC, DOC, THMs, Hydrophobic &amp; Hydrophilic fractions using LC-OCD-UVD-OND (Paper II)</td>
</tr>
</tbody>
</table>

**Fig. 13. Head loss curves at hydraulic loading rates of 3.4 m/h and 6.8 m/h (Paper III).**
of chlorophyceae (Fig. 14) and cyanobacteria (Fig. 15), respectively. Elsewhere, *Anabaena* and *Oscillatoria* were found to be the most dominant cyanobacteria at the surveyed drinking water treatment plants (AWWA, 2004). Some species of *Microcystis*, *Oscillatoria* and *Anabaena* have been reported to produce hepatotoxins (WHO, 2011) while *Chlorella*, *Closterium*, *Oscillatoria* and *Anabaena* are listed as filter-clogging algae (APHA, AWWA and WPCF, 2005). This is why it is important to remove intact cells of algae to avoid release of toxins in the water that may not easily be removed by subsequent processes especially in the developing world. Removal efficiencies varied depending on the algae genera (Paper III). Chlorophyceae was reduced by 73% and 65% in the sand and volcanic ash-sand filters, respectively. These were within range of chlorophyceae removal recorded in a sand filter by Demir & Atay (2002) although in their case there was pre-treatment of the incoming water by coagulation followed by sedimentation. However, while cyanobacteria were reduced by about 15% in the volcanic ash/sand filters, they increased in sand by 19%. The increase in sand was mainly contributed by *Anabaena* genera (Paper III). Consequently, the overall removal efficiencies for algae cells were 18% and 35% in the sand and dual media columns, respectively.

The increase in *Anabaena* cells would probably explain the shorter filter runs observed in the sand filters than in the dual media filters. Removal efficiencies of *Microcystis* cells greater than 99% were observed in both filters. The removal efficiencies observed are within the same range of studies carried out on pre-treated water (Vlaski et al., 1996; Drikas et al., 2001; Jurczak et al., 2005; Dugan & Williams, 2006). Given the differences in removal rates of algal cells, there was no significant difference in colour and turbidity of the filtrate from the volcanic ash-sand and sand columns (Colour: $p = 0.871 > 0.05$; Turbidity: $p = 0.067 > 0.05$). In addition, doubling the hydraulic loading rate did not give rise to change in the filtrate quality from both the sand and the ash-sand columns. However, this affected the head loss development in both filters. Quantification of algae on the media after doubling the loading rate, indicated higher number of *Anabaena* and *Chlorella* cells on sand than on volcanic ash whereas *Closterium* and *Oscillatoria* existed on sand only (Paper III). This also probably indicates preference of certain algae genera for different growth conditions or media and probably explains too short filter runs obtained in the mono media filters than in the dual media filters.
5.3. Removal of Iron and NOM co-existing in a Water Source

5.3.1. Horizontal roughing filtration with pumice as media

DOC and iron removal

Application of horizontal roughing filtration systems has been limited in most cases to turbidity and suspended solids removal. In this study, the performance of a horizontal roughing filter with pumice as media (HRFP) was investigated (Paper III). Few studies have made investigations on the possibility of using a roughing filter as a pre-treatment unit to remove NOM or/and iron where they co-exist. Average DOC removal of 27% was recorded. Corresponding reductions of total iron and ferrous iron of 39% and 89% respectively, were recorded. A comparison with similar studies that have been carried out elsewhere is presented in Table 8.

Tobian & Fazeli (2004) using a simple HRF with addition of 60 – 70 mg/l of powdered activated carbon (PAC) achieved removal of 75% TOC. In their study, synthetic water was used and the impact of PAC on the performance of the HRF is not clearly reported. Gehlen & Collins (2005) achieved less removal than observed with the HRFP. This study probably indicates that it is not only the particle sizes and flow regimes that affect the performance of roughing filtration systems but also the filter media characteristic plays a major role. It would be argued that less removals of organic material than observed in the HRFP were achieved by

Table 8: Comparison with other studies that have been done on roughing filtration systems elsewhere.

<table>
<thead>
<tr>
<th>Loading rate (m/h)</th>
<th>Parameters</th>
<th>Removal (%)</th>
<th>Roughing filter type</th>
<th>Media type</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>TOC</td>
<td>75</td>
<td>PAC + HRF (pilot scale)</td>
<td>Gravel</td>
<td>Tobian &amp; Fazeli (2004)</td>
</tr>
<tr>
<td>1 – 1.2</td>
<td>Iron</td>
<td>85</td>
<td>VRF (pilot scale)</td>
<td>Gravel</td>
<td>Pacini et al. (2005)</td>
</tr>
<tr>
<td></td>
<td>Manganese</td>
<td>95</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.45</td>
<td>TOC</td>
<td>12</td>
<td>Ozonation + VRF + SSF</td>
<td>Gravel</td>
<td>Gehlen &amp; Collins (2005)</td>
</tr>
<tr>
<td></td>
<td>DOC</td>
<td>13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.91</td>
<td>TOC</td>
<td>18</td>
<td>PACI + VRF + SSF</td>
<td>Gravel</td>
<td>Gehlen &amp; Collins (2005)</td>
</tr>
<tr>
<td></td>
<td>DOC</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.45</td>
<td>TOC</td>
<td>0</td>
<td>VRF + SSF</td>
<td>Gravel</td>
<td>Gehlen &amp; Collins (2005)</td>
</tr>
<tr>
<td></td>
<td>DOC</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.80</td>
<td>DOC</td>
<td>27</td>
<td>HRF (pilot scale)</td>
<td>Pumice</td>
<td>Paper IV</td>
</tr>
<tr>
<td></td>
<td>Total iron</td>
<td>39</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ferrous iron</td>
<td>89</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Gehlen & Collins (2005) because they used up-flow roughing filters (VRF). However, the application of PACl and Ozone before the VRF makes the HRFP more appropriate. Removal of ferrous iron was comparable with that obtained by Pacini et al. (2005). However, unlike ferrous iron, there was a low removal of total iron. This can probably be explained by the fact that Fe(III)-NOM complexes are generally thermodynamically favoured in oxygenated surface waters at circum-neutral pH with NOM stabilizing ferrie hyd(oxide)s as colloids (Liang & Morgan, 1990; Amirbahman & Olson, 1995). Hence removal of total iron would be determined too by the extent by which NOM is removal. Processes commonly applied to water with relatively high levels of both iron and NOM constitute treatment involving aeration, coagulation, lime treatment, settling and sand filtration at controlled pH range of 8.5 and 9.6. Therefore, application of the HRFP can be an alternative to such processes involving use of chemicals especially for the small water treatment plants.

Impact on the subsequent coagulation process and THMFP

To assess the character of NOM removed in the HRFP, comparison of the rate of THM formation in raw water and the HRFP filtrate was made (Fig.16 and 17). It was observed that part of the very reactive component of NOM to form THMs was removed resulting into a mean reduction in THMFP of 35% after 1 hour and 29% after 6 hours (Paper IV). The residual DOC in the coagulated raw water and the coagulated HRFP filtrate indicate that there is a fraction of NOM that is not amenable to removal under the conditions of the experiment. This is in agreement with the observation made by Edwards et al. (1996) that at higher oxide surface concentrations, the sorptive removal of TOC becomes less sensitive to sorbent dose and ultimately reaches a maximum value that cannot be increased with higher surface concentrations. This would have happened due to the low alkalinity of the raw water compared to that of the filtrate. All the alkalinity in the raw water was consumed. On the other, the HRFP improved on the alkalinity with a residual of 5 mg/l at an alum dose of 50 mg/l. The lower DOC and THMFP observed with the filtrate would be as a result of improved alkalinity in the HRFP to 30 mg CaCO$_3$/l compared to an average of 14 mg CaCO$_3$/l of raw water.

5.3.2. Application of hydrogen peroxide with pumice

With the aim of improving on the performance of the HRFP, hydrogen peroxide was applied to both the original
pumice (OP) and pumice from the HRFP (HRFP-P). The batch experiments conducted using the OP as adsorbent resulted in DOC removal of 23% within 2 hours with no significant difference in removal at subsequent time intervals (Paper V). The combined use of peroxide with the OP and HRFP-P resulted in better removals (Fig. 18). DOC removals up to 30 and 70% at peroxide dose of 1000 mg/l were achieved with the OP and HRFP-P, respectively. The results indicate that the OP itself is an effective catalyst for the oxidative destruction of NOM and the performance of HRFP-P compared to OP indicated a change of the surface characteristics of OP while in use in the HRFP. The higher removal by the HRFP-P is due to the iron hydr(oxide) coating that developed on the surface of OP in the course of treating water containing iron species in the roughing filter (Paper V). Although the DOC removal with HRFP-P increased with increasing dose of the peroxide, this was not the case with the OP. There was no significant difference in removal at doses of 300 mg/l and 1000 mg/l. Further, the laboratory scale HRF with uncrushed HRFP-P resulted in DOC removals of up to 68% at peroxide dose of 300 mg/l (Fig. 19). The crushed HRFP-P could be expected to give better performance due to a bigger surface area but this was not the case. From the scanning electron microscopy, it was indicated that not all the surface of the crushed HRFP-P particles were covered with hematite hence low catalytic activity. The control unit provided DOC removals up to 20% at peroxide dose of 300 mg/l. This result is expected; since it is known that hydroxyl radicals are produced by peroxide in the presence of aqueous species of iron through the Fenton’s reactions that are effective in oxidizing NOM. The results are comparable with those from other studies carried with pumice coated with iron oxides. In their study, Kitis & Kaplan (2007) while using original pumice and hydrogen peroxide they achieved UV reductions up to 49%. Moreover, in their study, they coated pumice with external iron oxide sources.

The results indicate that three mechanisms could have simultaneously played role in the removal of NOM: a portion of NOM adsorbed onto iron hydr(oxide) coating on pumice; remaining NOM fractions in solutions further oxidized with hydroxyl radicals produced from the surface reactions among iron hydr(oxides) and the peroxide including Fenton reactions (due to presence of iron species in solution); adsorbed NOM fractions on iron hydr(oxide) surface sites oxidized by hydroxyl radicals thus allowing
regeneration of pumice for further NOM removal. Therefore the observation made by Lin & Gurol (1998) that direct mediation by aquatic Fe (II) and Fe (III) does not seem to be needed for the catalytic oxidation reactions to take place is contradicted.

5.4. Application of *Moringa oleifera* as a Coagulant Aid

5.4.1. Removal of colour, turbidity and DOC

The application of *M. oleifera* as a coagulant aid significantly affected the treated water quality. Doses of MOC-SC less than 110 mg/l resulted in increased colour and turbidity of the treated water (Paper VI). The trend was suddenly reversed beyond 110 mg/l with a dose of 230 mg/l resulting in reduction of colour and turbidity as high as 96% and 89%, respectively (Fig. 20). For most waters, coagulant doses have been determined basing on turbidity but this might not be right for all types of water sources especially those with high levels of NOM and low turbidity. Therefore, in this study even though the lowest turbidity was achieved at a dose of 170 mg/l, MOC-SC dose of 230 mg/l was considered the optimum for NOM removal. Alum gave residual turbidity and colour values of 1.22 NTU and 20 PtCo at an optimum dosage of 50 mg/l, which values are comparable with those obtained with MOC-SC as a primary coagulant. Using alum with MOC-SC as a coagulant aid reduced the optimum dosage of alum from 50 to 30 mg/l to give the same level of residual colour and turbidity. The optimum dosage of MOC-SC as coagulant aid was found to be 100 mg/l. In all cases turbidity and colour values were less than values recommended by the WHO. Similar results were obtained at a pilot scale water treatment plant used to treat turbid surface water with processed *M. oleifera* seed and alum as primary coagulants (Muyibi & Alfugara, 2003). However, in their study they used *M. oleifera* coagulant extracted with distilled water. Similarly, Liew *et al.* (2006) compared the performance of *M. oleifera*, alum and mixture of *M. oleifera*/alum in turbidity reduction and *M. oleifera*/alum mixture recorded the lowest turbidity value. Therefore, results from this study are in agreement with findings from other studies that established that use of *M. oleifera* as a coagulant aid with alum resulted in better performance. It should, however, be noted that such studies focused on turbidity reduction. In this study (Paper VI), it has been shown that not only turbidity is improved but also removal of DOC and iron is improved. A combination of alum with MOC-SC reduced DOC concentration from 15 mg/l to 7.9 mg/l representing 47% removal (n = 6). In their research, Bawa *et al.* (2001) found that although performance of *M. oleifera* Lam seeds as a primary coagulant was poor, it could be used as adjuvant during the coagulation of humic acid solutions by ferric chloride and that the effect was obvious at low concentrations of the chemical coagulant (less than 60 mg/l). Probably, the same applies to MOC-SC with alum in the reduction of DOC in the clarified water while MOC-SC fails as a primary coagulant.

5.4.2. Iron removal

Residual iron values less than 1.0 mg/l were obtained with MOC-SC doses above 120 mg/l, 1.38 mg/l with MOC-SC as coagulant aid and 3.05 mg/l with alum alone (Fig. 21). MOC-SC as a primary coagulant gave the lowest residual iron concentration with values less than the WHO recommended value of 0.3 mg/l at dosages of 220 mg/l and above. The average residual iron concentrations in the control jar were 10.1, 9.81 and 9.61 mg/l for alum, alum and MOC-SC as coagulant aid and MOC-SC as primary coagulant, respectively. Thus aeration contributed about 7–10% removal of iron. Therefore a combination of alum with MOC-SC as coagulant aid would give a better option in the removal of iron and avoid the formation of THMs due to pre-chlorination.

5.4.3. Impact on taste of treated water

The use of MOC-SC resulted in an increase in the conductivity because of sodium chloride used in the extraction (Fig. 21). All the 10 people subjected to tasting the clarified water said it was salty. However,
after filtration and chlorination of the same water, all concluded that it tasted like tap water with chlorine. There was no salty taste in the water.

6. Conclusions

The removal of NOM was studied in order to reduce the generation of CBPs during water treatment. It was shown that it is possible to use indigenous materials in the removal of NOM and thus control the formation of THMs in drinking water treatment. Assessment of two existing plants was made to identify challenges in removal of NOM, batch and pilot scale experiments were done using volcanic ash, pumice and *M. oleifera* and with hydrogen peroxide. A summary of the findings obtained is presented below.

- It was found from the assessment of the plants that they had different challenges with respect to NOM removal. There were both operational and design handicaps at Ggaba II plant in that modification of the clarifiers and rapid gravity flow sand filters was necessary if water meeting both the national and international standards was to be tenable.
- Algal blooms (autochthonous NOM) was the major problem affecting the operation and performance of filters by frequent

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![Fig. 20. Effect of using MOC-SC, alum and alum with MOC-SC on a) turbidity and b) colour of the clarified water](image)

![Fig. 21. Effect of using MOC-SC, alum and alum with MOC-SC on a) pH and b) conductivity of the clarified water](image)
backwashing than recommended due to the shortened filter run lengths at Ggaba II. Algae were inadequately removed in the clarifiers and ended up together with other flocs into the filters. The algal problem was reflected by the significant change in the quality of raw water with an increase in the colour of about two folds at the intake works for the period under consideration.

- The physical and chemical characteristics of the volcanic ash indicated that it meets the requirements for a filter material and can thus be used as filter medium in a dual media filter system. Higher filter run lengths were obtained in the dual media columns than in the mono media columns which is attributed to the characteristics of the volcanic ash providing more storage capacity for the suspended particles than the sand. Converting the rapid flow gravity sand filters into dual media systems is an option that could improve on the filter run length. However, this is sustainable if done hand-in-hand with water quality management to reduce algal bloom at the source.

- There were different removal rates for the algal genera in the mono and dual media with the later performing better in the removal of algae. The diverse propagation of algae genera in different filter media arrangement would be used as a tool for removal of target genera. A dual media filter with volcanic ash-sand would also be an option in the pre-treatment of raw water containing algae, especially in the developing world where the operation and maintenance of energy intensive options like membrane filters and dissolved air flotation are a challenge. The application of chemicals would lead to cell lyses thus releasing of algal toxins that cannot easily be removed in most of the existing processes.

- High levels of THMs were formed at Boma plant and were not adequately reduced at the subsequent treatment units. Pre-chlorination led to an average increase in THM concentration of over 4000%. Therefore, it is not advisable to pre-chlorinate raw water from Nabajjuzi River.

- A large fraction of NOM at Nabajjuzi River was found to be hydrophilic in nature and was poorly removed by the coagulation process as indicated by the insignificant variance of NOM character and concentration after each of the unit processes. This indicated the inadequacy of the existing treatment train in the effective reduction of NOM and the need to modify the unit processes taking into consideration its character.

- Pumice and *M. oleifera* were found to be effective in the treatment of water where NOM co-exists with iron. DOC removals of up 27% were achieved in a horizontal flow roughing filter with pumice in its natural form as media while ferrous iron removals were as high as 89%. The reduction of the THMFP and iron both at the pre-treatment level and after coagulation indicated the role of a horizontal roughing filter with pumice in reducing the reactive component of the NOM that forms CBPs. *M. oleifera* extracted with a salt solution worked well as coagulant aid with alum resulting in DOC removal of up to 47%. In addition, DOC removals up to 70% were achieved when a combination of pumice and hydrogen peroxide was used. Therefore, with pumice as media, roughing filters could be used for pre-treatment of water with both high levels of NOM and iron other than high levels of turbidity and suspended solids for which they have been known to reduce.

The results from the study are proven, low-cost interventions that have the potential to improve on the provision of safe water to the communities in the developing world. The studied methods can be transferred to other areas of the region after trials at full scale levels. To achieve this goal, and to surpass it, will require continued collaboration, research and development, and investment. It is our best hope for rapidly increasing access to safe drinking water and reduce the burden of death or sickness arising from waterborne diseases in developing countries.
7. Future Research

The study was carried out to investigate appropriate measures or treatment methods for removal of NOM with minimal formation of by-products and consequently pumice, both in the roughing filter with larger grain sizes at pilot scale and with smaller particles at laboratory scale. The performance was better with addition of hydrogen peroxide. However, the interaction of the NOM, aquatic iron and the pumice surface was not investigated in this research and therefore the following areas are proposed for further research:

- Process analysis (mechanisms involved) and optimization of horizontal flow roughing filtration with pumice as media and the influence of hydrogen peroxide at both laboratory and pilot scale levels. This would be followed by testing and evaluation of full scale application with the aim of transferring the technology elsewhere in the region.

- Determination of the performance of the coagulants at variable pH/alkalinity with respect to NOM removal (TOC/DOC, UVA254); characterisation of the NOM before and after treatment with the coagulants and after filtration through a dual media bed of volcanic ash and sand should also be assessed.

- Characterisation of natural organic material in the raw water and optimisation of the coagulation process for their removal using the indigenous materials, in this case *M. oleifera* and volcanic ash should be done. Assessment of impact of filtration and chlorination of water treated by *M. oleifera* should also be done.
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Removal of natural organic matter and trihalomethanes formation control in water treatment


OTHERS


