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CIV 4200: CIVIL ENGINEERING PROJECT II

FINAL YEAR PROJECT REPORT

ASSESSING THE PERFORMANCE OF AN ANAEROBIC BAFFLED REACTOR AND A CONSTRUCTED WETLAND WITH DIFFERENT MEDIA IN GREYWATER TREATMENT

BY

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Submitted in Partial Fulfillment of the Requirements for the Award of a Degree of Bachelor of Science in Civil Engineering

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DECLARATION

We declare that the work presented in this report is original and has never been presented for award to any academic institution of higher learning. We confirm that where consultations were made either from publications or works of others, it has been cited in this report.

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DEDICATION

We dedicate this report to our loving families and friends for their invaluable support and financial assistance during the course of this research project. We also dedicate it to our lecturers at the School of Engineering, Makerere University who have enabled us to reach this milestone of education.

ACKNOWLEDGEMENT

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We thank the Almighty God for keeping us in good health throughout our academic journey.

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LIST OF ACRONYMS

ABR	-	Anaerobic Baffled Reactor
BOD	-	Biochemical Oxygen Demand
COD	-	Chemical Oxygen Demand
CW	-	Constructed Wetland
FC	-	Faecal Coliforms
HF	-	Horizontal Flow
N: P	-	Nitrogen to Phosphorus ratio
SAR	-	Sodium Adsorption Ratio
SDGs	-	Sustainable Development Goals
TDS	-	Total Dissolved Solids
TN	-	Total Nitrogen
TP	-	Total Phosphorus
TS	-	Total Solids
TSS	-	Total Suspended Solids
VF	-	Vertical Flow

LIST OF EQUATIONS

ABSTRACT

Wastewater has been mainly split into two main categories; black water and greywater. Greywater is the most abundant form of wastewater; it has far reaching effects on the environment through pollution. However, if managed well can be a resource with so many applications since its reuse can promote efficient and sustainable use of the limited water resources.

A treatment system was set up at Africa Hall in Makerere University to treat greywater discharged from kitchen. The system consisted of an anaerobic baffled reactor (ABR) pre-treatment system and a constructed wetland secondary treatment. The constructed wetland consists of different filter media horse tail reed floating mat, plastic and pumice. Greywater from the kitchen was characterised to establish the quality and it was observed not to be safe for disposal.

The systems were monitored for treatment efficiency across different parameters for a period of 8 weeks March to December. Samples were collected for laboratory analysis from the five collection points to assess the quality of water being discharged and the performance of the system. Flows were measured to establish the hydraulic load on the system and plant girths for macrophytes were also taken.

The ABR achieved removal efficiency of 96.37 ± 469.56% for TSS, 34.93 ±2.94% for TP,34.91 ±31.45% for TN, 97.29 ± 588.57% COD and 93.21 ±551.82% for BOD_5. The different media in the constructed wetland achieved removal efficiencies of 82.70 ± 18.70% BOD_5 removal for the horsetail reed floating mat, 78.25 ± 10.25% BOD5 removal for plastic and 82.86 ± 47.73% BOD5 removal for pumice. For COD removal, the horsetail reed floating mat achieved 41.21 ± 3.12%, 5.77 ± 3.87% for plastic and 49.99 ± 9.72% for pumice. For suspended solids, the horsetail reed floating mat achieved a removal efficiency of 92.34 ± 3.52%, plastic achieved -12.53 ± 3.67% while pumice achieved -45.52± 19.47%. Overall, the findings also highlighted that pumice achieved the highest removal efficiency for the various pollutant parameters.

The treated greywater was also observed to meet some reuse criteria for different applications such as irrigation and toilet flushing.

There is therefore need to consider greywater treatment as a measure of reducing greywater environmental pollution by wastewater. The pumice media can be an efficient treatment media in the constructed wetland system and achieve proper treatment.

CHAPTER 1 - INTRODUCTION

1.1 Background

Water is an essential resource for life and good health. However, the increasing population growth in urban settlements has created unprecedented challenges. One of the many challenges, according to UNDESA (2014), is provision of water and sanitation. The increase in demand for water has led to a consequential increment in the abstraction of fresh water for a myriad of human purposes ranging from personal hygiene, agriculture to industrial uses. Being the second-driest continent, Africa has about 9% of global renewable water resources which, unfortunately, is meant to support 15% of the global population (Hongtao, et al., 2013). This means that the available water sources, in the face of adverse climate changes, cannot sustainably serve the ever-growing human population. It is on such criterion that the United Nations called the world to action with the Sustainable Development Goals (SDGs) in 2015. Some of these goals focus on the urgency of man learning to flourish within the means of the earth such as the sixth SDG which aims at ensuring availability and sustainable management of water and sanitation. One of the specific targets of this goal (Target 6.3) is to "Improve water quality, wastewater treatment and its safe reuse" the world-over.

Wastewater comprises mainly black and grey water. Both these wastewater streams ought to undergo treatment prior to disposal or reuse. This study, however, in light of the sixth SDG, focuses on the treatment of greywater particularly kitchen greywater as discussed in later sections. Grey water can be defined as the total volume of wastewater generated from washing food, clothes and dishware, as well as from bathing. It accounts for 65% of wastewater generated in a household (Tilley, Ulrich, & Luthi, 2014). With ample treatment, grey water can be a source of a reliable and consistent supply of non-potable water which can be used for agricultural purposes and other human needs that do not require water with a drinking water quality (Environment Agency, 2011).

A number of operational wastewater treatment plants in developing countries discharge wastewater with concentrations above those stipulated by the national environmental regulatory bodies (Gunawardana, Jayakody, & Bandara, 2016). This can be attributed to lack of sufficient and appropriate treatment systems as well as lack of proper process monitoring and maintenance activities.

This study sought to assess the performance of a greywater treatment system located at Africa hall, Makerere University. The greywater treatment system was comprised of an Anaerobic Baffled Reactor (ABR) and a Constructed Wetland (CW). By definition, an ABR is an improved septic tank with a series of baffles under which the wastewater is forced to flow (Tilley, Ulrich, & Luthi, 2014).The baffles increase the contact time of the wastewater with the active biomass (sludge) at the bottom which results in improved treatment. The constructed wetland uses an intricate blend between vascular wetland plants (macrophytes) and the medium in which they grow to cleanse the wastewater that flows through it. The constructed wetland in this study used horsetail reed as the macrophyte growing in pumice and plastic as the substrates. It treated effluent from the ABR which acted as a pre-treatment system.

1.2 Problem statement

Greywater is commonly discharged into drainage channels, onto streets, open grounds, or into natural water bodies following insufficient or no prior treatment (Morel & Diener, 2006). This practice was also commonplace at the Africa hall kitchen where an average 100 litres of greywater are produced daily. Figure 1-1 below shows greywater being disposed of openly into the environment at the Africa hall kitchen prior to the construction of an on-site treatment plant downstream of the kitchen.

Figure 1-1: Disposal of raw greywater at Africa hall kitchen

According to Ridderstolpe (2004), greywater is primarily comprised of biodegradable organic compounds, nutrients, metals and pathogens. Metals and pathogens pose great risks to human health once contact is made whereas nutrients are catalytic in the process of eutrophication.

In Uganda, conventional off-site wastewater treatment plants have been established so as to minimize on the discharge of poorly treated/un-treated wastewater. Notably, in Kampala, there is Lubigi Sewage Treatment Plant and Bugoloobi Wastewater Treatment Plant. However, due to a limited coverage of the sewer system, most of the generated wastewater does not reach these treatment plants. Andersson, *et al* (2016) report that in some sub-Saharan countries such as Kenya, Uganda and Malawi, only around 10% of the populations are connected to a sewer system. It is on this premise that the construction of on-site treatment systems to curb wastewater pollution at its source becomes a necessity.

1.3 Objectives

The main objective of this study was to assess the performance of an Anaerobic Baffled Reactor and Constructed Wetland with different media in greywater treatment, a case of the kitchen at Africa Hall in Makerere University.

The specific objectives of the study were;

(i) To determine the characteristics of greywater discharging from the Africa Hall kitchen.

(ii) To evaluate the performance of a greywater treatment plant comprising an Anaerobic Baffled Reactor as a pre-treatment system and a constructed wetland comprised of different substrate media.

(iii) To assess the viability of the treated greywater for various reuse options.

1.4 Scope of study

The study focused on investigating the performance of an anaerobic baffled reactor and a constructed wetland in the treatment of kitchen greywater. The quality characterization of the greywater was limited to selected physical (temperature, odour, turbidity), chemical (pH, metals, BOD_5, total nitrogen total phosphorus) and bacteriological (faecal coliforms) parameters of the greywater.

The treatment plant in this study is located at Africa Hall within Makerere University on the northern side of the campus (Figure 1-1). The plant receives greywater from the kitchen that serves the hall.

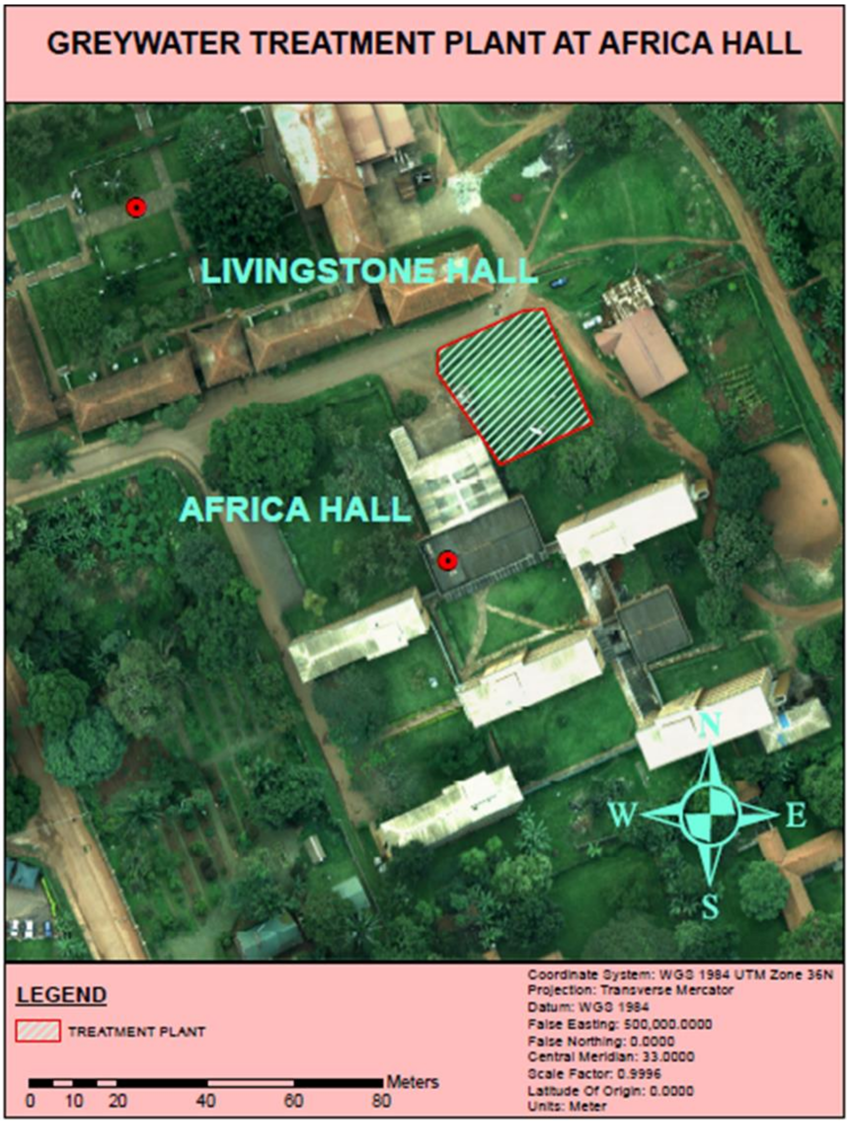

Figure 1-2: Map showing the location of the greywater treatment plant behind Africa Hall

1.5 Significance of the study

The study provides information on the efficiency of using a combination of an anaerobic baffled reactor as a pre-treatment system and a constructed wetland planted with horsetail reed as a tertiary system in the treatment of greywater. The novelty of this study is further highlighted by the assessment of the treatment efficiency of the substrate media used namely; plastic, pumice and the horsetail reed floating mat. Lastly, the pollutant removal efficiencies of the treatment plant that are discussed in Chapter 4 add to the body of knowledge that informs the plausibility of greywater reuse in toilet flushing and agriculture.

CHAPTER 2 - LITERATURE REVIEW

2.1 Introduction

An estimated 90 per cent of all wastewater in developing countries is discharged untreated directly into rivers, lakes or the oceans (Corcoan, et al., 2010). This has had a negative impact on human and environmental health such as spread of water borne diseases and eutrophication respectively. It is, therefore, imperative that all wastewater undergoes sufficient treatment prior to disposal into water bodies and/or the soil. This is a step towards the achievement of the previously alluded to target indicator of the sixth SDG (Section 1.1).

Most conventional off-site wastewater treatment systems are expensive, resource intensive and often require high technical capacities with regards to urban planning, construction, operation & maintenance (Mustafa, 2013). With the adoption of the Sustainable Development Goals (SDGs), the global village has committed to the urgency for alternative on-site wastewater treatment solutions that better fit local needs and currently existing capacities. Some of these solutions include septic tanks, anaerobic baffled reactors, among others.

Wastewater defines all used water in homes and industries including storm water and runoff from lands, which must be treated before it is released into the environment in order to prevent any harm or risk it may have on the environment and human health (Edokpayi, Durowoju, & Odiyo, 2017). The major types of wastewater are clearly illustrated in Figure 2.1 (Edokpayi, Durowoju, & Odiyo, 2017).

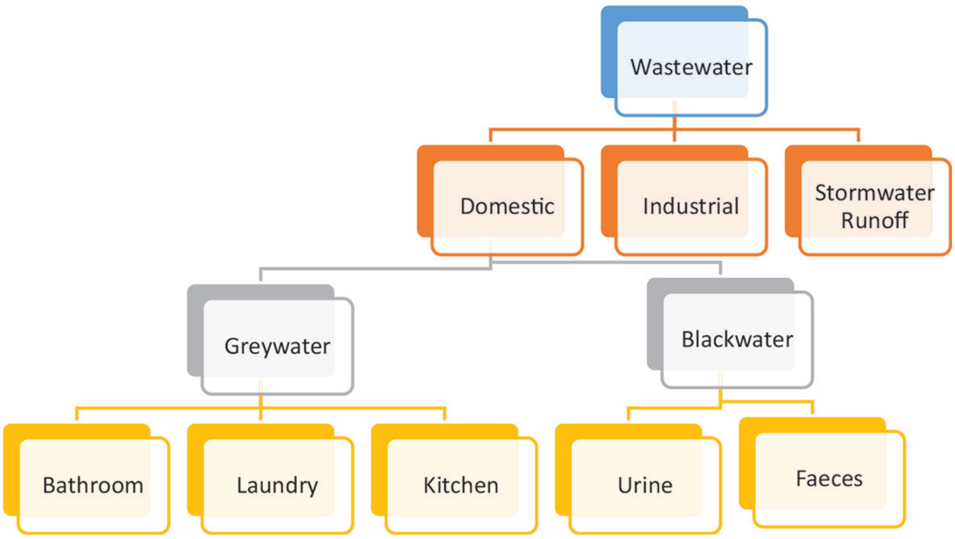

Figure 2-1: Types of wastewater

However, this study focuses on the treatment of domestic wastewater, precisely greywater from a kitchen.

2.2 Domestic Wastewater

Historically, domestic wastewater has been split into two main categories: blackwater and greywater (Boutin & Eme , 2017). Greywater includes all wastewater generated in the home, except toilet water which is considered as "blackwater" (Brain, Lynch, & Kopp, 2015). In some definitions of greywater (also known as sullage), the wastewater water discharged from kitchen sinks and dishwashers is not considered due to the presence of grease and oil, high organic content and increased microbial activity of the greywater which leads to oxygen depletion (PUB, 2014). Despite the existence of such literature, we go ahead to define the wastewater emanating from the Africa hall kitchen as greywater following the majority descriptions of what greywater is.

Albalawneh & Chang (2015) continue to classify greywater into light and dark basing on the source, as shown in Figure 2-2.

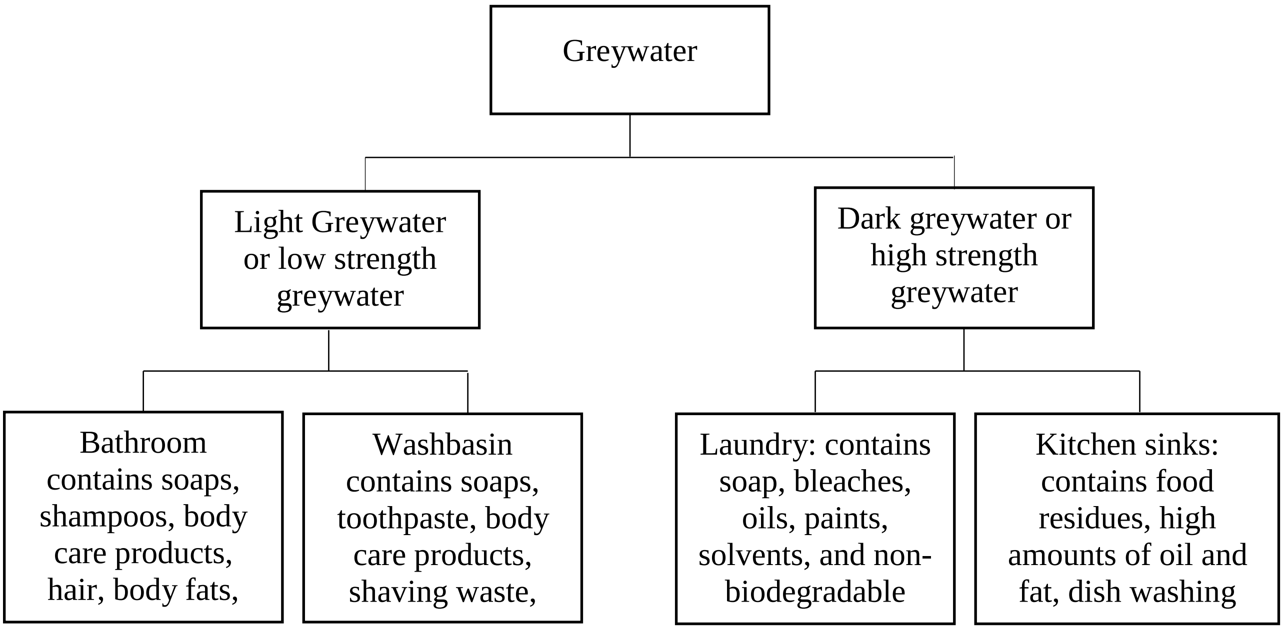

Figure 2-2: Classification of Greywater

In light of this study, the greywater encountered was dark greywater from kitchen sinks.

2.3 Nature and Quality of greywater

The physical, chemical, and microbial characteristics of greywater vary depending on a number of factors; from sources to the household composition as well as the cleaning and personal care habits of the residents (Marjoram, 2014).

According to Albalawneh & Chang (2015), studies from developing countries like Yemen and Amman show that 27% of greywater originates from the kitchen sinks and dishwashers, 47% originates from the wash basin, bathroom, and shower, and 26% originates from laundry and the washing machine. A study carried out by Kulabako, Ssonko, & Kinobe (2011) in Kawaala, Uganda indicated that the greywater was characterized by high BOD_5 (>30 mg/l) and COD (>100 mg COD/l) as well as E.Coli (> 0 cfu/100 ml). These values necessitate treatment prior to disposal of the greywater in the environment. Bakare, Mtsweni, & Rathilal (2016), following a study in Durban (South Africa) further argue that greywater generated from household kitchens and that from the laundry is higher in organics and physical pollutants compared to bathroom and mixed greywater. The organics in the kitchen greywater can be attributed to the presence of food particles in it. On the other hand, the organics in laundry greywater can be attributed to the occurrence of organic micro-pollutants (OMPs) emanating from fragrances and dyes (Mohamed, et al., 2018).

The nature and quality of greywater depend on the volumes generated as well. In rural low populated settlements, where the total amount of water used is little, low volumes of high strength greywater are generated. On the other hand, in places where water consumption is high (highly populated urban settlements), the volume of greywater is greater but more diluted (Morel & Diener, 2006). However, this could also be attributed to the fact that rural areas have a low service coverage of piped systems such that during such studies, the amount of water captured is not accurately representative of the total amount of water utilized unlike in urban areas where what is captured is a relatively good representation of the utilized water due to a more comprehensive piped water system. As such, it is not impossible to find that despite the difference in greywater volumes generated in these two settlements, the strength of greywater is relatively similar.

The nature of greywater can be grouped into physiochemical and biological qualities as discussed in the subsequent subsections.

2.3.1 Physicochemical Characteristics of Greywater

Oteng-Peprah, Acheampong, & Vries (2018) associate the physical and chemical characteristics of greywater with the parameters which describe the physical appearance of greywater and the sources of the greywater respectively. A portmanteau of physical and chemical characterisation gives rise to the the term physio-chemical characteristics. The parameters under this concept are discussed below;

1. **Temperature**

The temperature of greywater is often higher than that of the water supply and varies within a range of 18-30°C (Morel & Diener, 2006). The higher temperatures can be attributed to the uses to which water supplied is subjected in the different greywater sources. In the bathroom and kitchen, warm water is used for personal hygiene and cooking. Washing machines generate heat while spinning the laundry. All this causes the resulting greywater to be of a higher temperature than the water that was supplied. These high temperatures may favour microbiological growth which is desirable for greywater treatment. On the other hand, they may cause precipitation of carbonates such as calcium carbonate ($CaCO_3$) and other inorganic salts which become less soluble at high temperatures and can reduce the permeability of the soil where the water is discharged untreated (Oteng-Peprah, Acheampong, & K.deVries, 2018).

2. **Turbidity**

Turbidity is caused by particles suspended or dissolved in water that scatter light making the water appear cloudy or murky. Turbidity is also affected by several factors namely; size, shape and composition of the particles (Minnesota Pollution Control Agency , 2008). Left-over food and soil particles from kitchen sinks, hair and fibres from laundry are sources of these turbidity causing particles in greywater. These particles and colloids may even result in physical clogging of pipes, pumps and filters used in treatment processes (Morel & Diener, 2006).

3. **pH**

The pH indicates whether a liquid is acidic or basic. Greywater from laundry activities exhibits a high pH due to the presence of alkaline materials in the used detergents (Peprah, Acheampong, & deVries, 2018). A 2016 study by Siggins *et al* showed that a pH greater than 7.5 is considered to be sub-optimal for soil health and may inhibit plant growth by limiting the availability of nutrients such as phosphorus, copper, iron, manganese, molybdenum and zinc. Kitchen greywater usually exhibits acidic conditions due to contamination with food fractions, oils and its degradation occurs more rapidly in anoxic conditions which makes it more acidic (Bakare, Mtsweni, & Rathilal, 2016).

4. **Odour**

When greywater is stored, it turns septic, giving rise to offensive odours and providing suitable conditions for microorganisms to multiply (WHO, 2006). Odors are usually caused by gases such as hydrogen sulphide and other products of decomposition of organic matter in anaerobic conditions.

5. **Oil and Grease**

This component is not as prominent in other sources of greywater as it is for the kitchen. This is obviously attributed to the fats from the food prepared therein. As soon as the kitchen greywater cools down, grease and fat coagulate and can cause mats on the interior of pipes and other surfaces (Morel & Diener, 2006). This matting reduces on the carrying capacity of pipes which consequently causes them to operate below their design hydraulic loads.

6. **Biochemical Oxygen Demand (BOD_5)**

Biochemical Oxygen Demand is defined as a measure of the amount of oxygen consumed by aerobic bacteria to breakdown organic matter in a wastewater sample over a 5-day period at a temperature of 20°C (Abdalla & Hammam, 2014). BOD_5 speaks to the concentration of organic matter in the wastewater stream. The higher the concentration of organic matter, the higher the amount of oxygen used by the bacteria to oxidise them hence a high BOD_5 value and vice versa. Its concentration is expressed in milligrams per litre of wastewater sample used (mg/l).

In a study carried out by Albalawneh & Chang (2015), observations that the BOD concentrations are within the range of 48-1,056 mg/l for dark greywater and 20-300 mg/l for light greywater were made. This can be attributed to the difference in sources for the two variances of greywater. Dark greywater derives its high organic content from the relatively large amounts of food residues washed into kitchen drains. The greywater encountered in this study had a relatively high BOD_5 values due to this.

7. Chemical Oxygen Demand (COD)

Chemical Oxygen Demand is the amount of oxygen necessary to completely oxidise all of the organic carbon in wastewater turning it into carbon dioxide and water (Gerba & Pepper, 2015). Its concentration is measured milligrams per litre as well.

The COD concentrations are within the ranges 50-2,568 mg/l for dark greywater and 55-633 mg/l for light greywater (Albalawneh & Chang, 2015). Dark greywater comprises higher COD concentrations due to the presence of surfactants from laundry powders and dishwashing liquids (Albalawneh & Chang, 2015).

8. COD/BOD ratio

The COD/BOD ratio indicates the level of biodegradability of a wastewater sample (Achour, 2016). Biodegradability of greywater is primarily dependent on the type of surfactants used in detergents and on the amount of oil and fat present in the greywater (Morel & Diener, 2006).

Achour (2016) highlights the following conclusions about greywater regarding various COD/BOD ratios;

- Less than 2 – Readily biodegradable
- Betweeen 2 and 4 – Moderately biodegradable although the process will be relatively slow
- Greater than 4 – Hardly biodegradable since the wastewater inhibits the metabolic activity of the aerobic bacteria

9. Nitrogen

Nitrogen in greywater originates from ammonia and ammonia-containing cleansing products as well as from proteins in meats, vegetables, protein-containing shampoos, and other household products (Morel & Diener, 2006). According to Imhof & Muhlemann (2005), the measured concentration value of total nitrogen in kitchen greywater is approximately 13-60 milligrams per litre in developing countries.

10. Phosphorus

Morel & Diener (2006) argue that dishwashing and laundry detergents are the primary sources of phosphorus in greywater. The measured concentration value of total phosphorus in kitchen greywater from developing countries is 3.1-10 milligrams per litre (Imhof & Muhlemann, 2005). The phosphorous removal processes in natural treatment systems include chemical precipitation, sedimentation, sorption and plant and microbial uptake (Dotro *et al*., 2017).

2.3.2 Microbiological characteristics of Greywater

Contrary to popular belief, greywater has traces of some rather harmful microbial pathogens such as viruses, bacteria, protozoa, and intestinal parasites (Morel & Diener, 2006). These pathogens originate from excreta of infected persons which is disposed into the greywater by way of hand washing after toilet use, washing of babies after defecation and also washing of vegetables and raw meat. The pathogens pose a significant threat to soil, crops as well as human beings who might accidentally ingest the helminths.

Imhof & Muhlemann (2005) reported the following ranges for microbiological parameters of greywater from kitchens in developing countries;

- Eschericia Coli (E-Coli) – (1.3×10^5 – 2.5×10^8) mg per 100ml
- Thermotolerant Coli – (0.2×10^6 – 3.75×10^8) mg per 100ml

From the greywater to be encountered in this study, such pathogens are expected to be found in the greywater following from washing of raw meat and vegetables as well as washing of hands.

2.4 Treatment systems of greywater

Treatment systems are used to reduce the level of contamination in the greywater before reuse or disposal into the environment. The method of treatment adopted by each system ranges from physical, chemical and biological as discussed in the subsequent subsections.

2.4.1 Physical treatment systems

Physical treatment of greywater is done by means of filtration. Filtration is often used as a pre-treatment system to remove as much TSS and COD in form of suspended solids as possible before further treatment (Peprah, Acheampong, & deVries, 2018). While solid particles get trapped within the filtration matrix, COD and BOD removal is assisted by a biofilm layer that eventually forms on the surface of the filtration medium (Yash, Vishnu, & Ming, 2013).

Some of the filtration media include membranes, sand and soil. These different filtration media yield varying contaminant removal efficiencies when treating wastewater. Their performances in treatment of greywater is summarised in Table 2.1.

2.4.1.1 Membrane Filtration

This refers to the retention of suspended solids as the greywater passes over a porous medium (membrane). There are various kinds of membranes which have been applied in the physical treatment of greywater such as nylon, ultra filtration membranes and nano-filtration membranes.

1. **Nylon sock membrane**

A low strength bath grey water treatment system used in a hotel in Spain, which used a nylon sock type filter followed by sedimentation and disinfection by hypochlorite addition. The study claimed that the reclaimed grey water could be used for toilet flushing under controlled working conditions such as a particular residual chlorine concentration in the toilet tank (Fangyue, Knut, & Ralf, 2009). The chlorine was meant to oxidise inorganic and organic matter in the cistern.

2. **Ultra Filtration Membrane**

The use of an Ultra Filtration (UF) membrane entails making use of pressure and concentration gradients to separate material from liquids. The pore sizes of the membranes play an important role on the treatment performance by creating said difference. A report by Fangyue, Knut, & Ralf (2009) cites the usage of a 0.05 μm pore size for the treatment of laundry grey water. The UF membrane provided a limited removal of the dissolved organics but an excellent removal of the suspended solids, turbidity and pathogens.

3. **Nano Filtration Membrane**

Nano filtration (NF) membranes utilise nanometer sized pores to retain contaminants. The permeate from the NF is well suited for all-purpose unrestricted reuse (Yash, Vishnu, & Ming, 2013).The performance efficiencies of these membranes were referrenced from (Fangyue, Knut, & Ralf, 2009) and (Yash, Vishnu, & Ming, 2013) represented in Table 2-1 as superscripts 1 and 2 respectively. Despite the tabulated performance efficiencies, membrane filtration is not widely used due to its high operating and maintenance costs (Fangyue, Knut, & Ralf, 2009). Furthermore, the membrane fouling due to degradation of retained solids makes this method less preferred.

2.4.1.2 Soil Filtration

Soil filtration refers to the retention of suspended solids and other contaminants from water in a soil medium as the water flows through the different soil layers. Due to the nitrification and de-nitrification reactions in the soil treatment system, nitrogen was eliminated effectively. Its efficiency in removal of other contaminants of greywater was reported by Fangyue, Knut, & Ralf (2009). as summarised in Table 2-1.

2.4.1.3 Sand Filtration

Sand filters trap suspended solids in their pore spaces as water flows through them. Friedler, Kovalio, & Ben-Zvi (2006) reported the use of a stand alone filtration unit in the treatment of light greywater from an eight storey high building with six flats per storey in Israel. This system comprised 0.7 m deep of quartz sand supported by a 0.1 m deep gravel layer (diameter 2.2 mm). Filtration rate was set at 8.3 m/hr. The performance of this system was tabulated in Table 2-1.

Table 2-1: Removal Efficiencies for Physical Treatment Systems

Physical Treatment Systems (Filtration)	Removal efficiencies for different parameters						
	COD	BOD	Turbidity	SS	TN	TP	TOC
Ultra-filtration membrane [1]		55.8%					
Nano-filtration membrane [2]	93%						84%
Nylon sock type [1]	54.4%		17.5%	57.7%	37.7%		
Soil	85%	83%		78%	78.7%	84.2%	
Sand	38%		46%				

From the values in Table 2-1, it can be concluded that physical treatment systems are not, as stand-alone systems, efficient at treatment of greywater to a level at which it can be disposed or reused. Therefore, there is need for subsequent treatment.

2.4.2 Chemical Treatment Systems

Chemical treatment methods are reported by Yash, Vishnu, & Ming (2013) as being efficient with light greywater and in some cases, laundry greywater. However very few chemical processes were reported for grey water treatments and reuses (Li, Wichmann, & Otterpohl, 2009). They can also be used with dark greywater as a final treatment step, following biological treatment. Some of the methods include; coagulation, ion exchange, photocatalysis and adsorption using granular activated carbon.

2.4.2.1 Ion Exchange

Fangyue, Knut, & Ralf (2009) reported use of the ion exhchange method where it was applied for shower grey water treatment. At optimal pH which conditions, magnetic ion exchange resin reduced the COD, BOD, turbidity, TN at efficiencies summarised in Table 2-2.

2.4.2.2 Photocatalysis

Photocatalysis with titanium dioxide (TiO2) catalysts is an efficient post-treatment for biological pollutants giving very high-quality water that could be used for groundwater recharge (Yash, Vishnu, & Ming, 2013). Photocatalysis is the use of a catalyst, UV light and an oxidant to oxidise organic pollutants in air or water. The photocatalytic stage assists in mineralising dissolved organics as well as partially degrading organic compounds (Yash, Vishnu, & Ming, 2013). A disinfection step is not required as photocatalysis can greatly reduce pathogens in water.

2.4.2.3 Coagulation

Coagulation is a process used to neutralize charges and form a gelatinous mass to trap (or bridge) particles thus forming a mass large enough to settle or be trapped in the filter (Ismail, Khulbe, & Matsuura, 2019). This can be done using materials termed as coagulants like Iron and aluminium salts. Coagulant chemicals with charges opposite those of the suspended solids are added to the water to neutralize the negative charges on non-settleable solids (such as clay and colour-producing organic substances). Once the charge is neutralized, the small suspended particles are capable of sticking together allowing particle collision and growth of flocs, which then can be settled and removed (by sedimentation) or filtered out of the water.

Natural coagulants originating from vegetables and seeds were in use before the wide scale use of chemical salts, but they have not been able to displace the use of chemical salts as the scientific grasp of their effectiveness and mechanism of action was lacking (Muruganandam, *et al*., 2017).

In a study by Lin, Lo, Kuo, & Wu (2015) for on-site domestic greywater treatment using coagulation, COD declined as the dosage of alum increased to 25 mg/L. The resultant removal of the COD is as shown in Table 2-2. Increasing the dosage of released alum to 50 mg/L did not increase COD removal efficiency.

Table 2-2: Removal Efficiencies for Chemical Treatment systems

Chemical Treatment Systems	Removal efficiencies for different parameters			
	COD	BOD	Turbidity	TN
Coagulation	60%			
Photocatalysis		65%		
Ion Exchange	65%	83.9%	82.5%	15%

2.4.3 Biological Treatment Systems

Biological treatment systems rely on organisms such as bacteria (aerobic or anaerobic) to break down organic matter in greywater using their normal cellular processes. There are a number of such systems applied in the treatement of greywater as discussed in the subsequent sub-sections.

2.4.3.1 Membrane Bioreactor (MBR)

The membrane bioreactor (MBR) combines membrane filtration and biodegradation of the trapped solids in its treatment mechanism.

Fangyue, Knut, & Ralf (2009) reported a study on a submerged MBR (polyethylene, pore size 0.4 μm) for low strength bath grey water treatment. The contaminant removal efficiencies of the study are summarised in Table 2-4. The effluent was colourless and odourless and free of SS. This study demonstrated that biological degradation removed most of the pollutants and membrane separation further eliminated the rest of the pollutants, thus ensuring a stable and excellent effluent water quality.

2.4.3.2 Anaerobic Baffled Reactor (ABR)

An ABR is a septic tank like unit comprised of several compartments in series separated by baffles. ABRs can be constructed out of concrete, masonry, or prefabricated fibreglass (Tayler, 2018).

Performance efficiency

ABRs have also been observed to achieve up to 77% BOD_5 removal, 73.4% TSS removal (Nasr, Doma, & Nassar, 2009) and the treatment varies for different retention times compared to sedimentation tanks which achieve only up to COD and BOD removal of 15% (Shegokar, Ramteke, & Meshram, 2015). This is the case that formed the basis for selecting the ABR for the given greywater.

2.4.3.3 Constructed wetland

Constructed (treatment) wetlands are engineered systems designed to optimise processes found in natural environments for wastewater treatment (Dotro, *et al*., 2017). This aspect of their functionality makes them both environmentally friendly and sustainable options for wastewater treatment. A constructed wetland is a shallow basin planted with a suitable plant (referred to as a macrophyte) in in a suitable substrate or even directly in the water it treats. The selected vegetation must be tolerant of saturated conditions (UN-HABITAT, 2008). These wetlands are used as secondary or tertiary treatment units which implies that the influent wastewater into them first undergoes pre-treatment in settling tanks or technical treatment plants (Gauss, 2008).

According to UN-Habitat (2008) the major constituents of a constructed wetland include;

- Basin
- Substrate
- Macrophytes (plants)
- Liner
- Inlet/outlet arrangement system

2.4.3.3.1 Substrates

As mentioned in sub section 2.4.3.3, substrates used for CWs include sand, gravel as well as crushed rock and synthetic materials like slag. Substrate media have been used in constructed wetlands, not only for structural support of the plants but also to enhance nutrient removal (Tatoulis, *et al*., 2017)..They do so through support of biochemical and chemical transformation of pollutants, provision of sites for microbial growth which remove organic matter and also allowing the physical filtration of the wastewater (Qomariyah *et al*, 2016).

In order to investigate the performance of different media (Lima, et al., 2018), used gravel, light expanded clay and clay bricks. At the end of the experimental period (296 days), the planted system filled with bricks achieved the highest mass removal for COD (211.68 g), compared to the other systems. The characteristics of the substrate (porosity) has also been observed to contribute to clogging of wetlands which reduces pore volume of the media hence affecting the performance (Tatoulis *et al*., 2017). These studies highlight the effect of media type and characteristics on treatment efficiency and performance of a constructed wetland. In this study, novel media like plastic and pumice were used for greywater treatment to ascertain their performance in pollutant removal.

2.4.3.3.2 Macrophyte plants

The term macrophyte includes vascular plants that have tissues that are easily visible (Kadlec & Wallace, 2009). Wetland plants play several important roles in treatment wetlands. Primarily, their roots and rhizomes provide attachment sites for microbial biofilms increasing the biological activity per unit area (Dotro, *et al*., 2017).. They also significantly transport oxygen to the root zone to allow the roots to survive in anaerobic conditions (Qomariyah, *et al*., 2016). This oxygen, however, is greatly competed for by aerobic bacteria as well as the microbial growth on the roots of the macrophytes during the decomposition process. This eventually leads to a reduction in the amount of available oxygen thus causing acidic conditions that can cause dieback of the plant which returns absorbed nutrients back into the water (Rehman, *et al*., 2019). This process, though it is in the long term, reduces the treatment efficiency of the wetland. In spite of the fact that the most important removal processes in constructed treatment wetlands are based on physical and microbial processes, the macrophytes possess several functions in relation to the water treatment. They are partly responsible for the removal of soluble nutrients such as nitrogen and phosphorus through plant uptake for their own growth. The comparison of treatment efficiency of vegetated Horizontal Flow (HF) CWs and unplanted CWs is not unanimous but most studies have shown that systems with plants (macrophytes) achieve higher treatment efficiency (Vymazal, 2011) and this could be attributed to the role played by these in nutrient removal.

According to UN-HABITAT (2008), vegetation to be planted in constructed wetlands should fulfil the following criteria;

- Deep root penetration, strong rhizomes and massive fibrous root.
- Considerable biomass or stem densities to achieve maximum translocation of water and
- Assimilation of nutrients.
- Maximum surface area for microbial populations.
- Efficient oxygen transport into root zone to facilitate oxidation of reduced toxic metals and support a large rhizosphere.

According to Kadlec & Wallace (2009), wetland plants can be categorized by their growth habit with respect to the wetland water surface as:

- Emergent soft tissue plants
- Emergent woody plants
- Submersed aquatic plants
- Floating plants
- Floating mat

Emergent soft and woody plants are used in sub-surface flow wetlands and all the categories can be used in the free-water surface wetlands. A description of emergent, floating and submerged macrophytes follows below;

1. **Emergent macrophytes**: These are the dominating life form in wetlands and marshes, growing within a water table ranging from 50 cm below the soil surface to a water depth of 150 cm or more. In general, they produce aerial stems and leaves and an extensive root and rhizome-system. This life form comprises species like *Phragmites australis* (Common Reed), *Glyceria* spp. (Mannagrasses), *Eleocharis* spp. (Spikerushes), *Typha* spp. (Cattails), *Scirpus* spp. (Bulrushes), *Iris* spp. (Blue and Yellow Flags) and *Zizania aquatica* (Wild Rice).

2. **Floating-leaved aquatic macrophytes**: These include both species which are rooted in the substrate, e.g. *Nymphaea* spp. and *Nuphar* spp. (Waterlilies), *Potamogeton natans 4* (Pondweed), and *Hydrocotyle vulgaris* (Pennyworth), and species which are freely floating on the water surface, e.g. *Eichhornia crassipes* (Water Hyacinth), *Pistia stratiotes* (Water Lettuce) and *Lemna* spp. and *Spirodella* spp. (Duckweed).
3. **Submerged aquatic macrophytes**: These have their photosynthetic tissue entirely submerged but usually the flowers exposed to the atmosphere. Two types of submerged aquatics are usually recognised: the elodeid type (e.g. *Elodea*, *Myriophyllum, Ceratophyllum*), and the *isoetid* (rosette) type (e.g. *Isoetes*, *Littorella*, *Lobelia*).

The commonly used macrophytes in wetlands include common reed (*Phragmites australis*), Bulrushes (*Scirpus* spp) and species of the genera Typha (*latifolia*, *angustifolia*, *domingensis*, *orientalis* and *glauca*) (Vymazal, 2011). The selection of plants depends on the climate, method of introduction of the plant, cost and availability of planting stock, plant size, rate of colonization of the selected plant species, water quality, maintenance requirement, availability of macrophytes locally and environmental conditions of the area (Kadlec & Wallace, 2009; Shah, *et al*., 2014).

2.4.3.3.2.1 Performance of macrophytes

Literature indicates that the most frequently used plant in constructed wetlands around the globe is *Phragmites australis* (common reed) due to its widespread natural distribution (Vymazal, 2011; Hoffmann, *et al*., 2011). Ajibade & Adewumi (2017) identified that *Phragmites australis* achieved a 10.72% COD removal efficiency for raw wastewater of 35.45mg/l and a 12.78% removal for raw wastewater of 48.67mg/l in laboratory scale ponds.

While using water hyacinth, Shah, *et al*., (2014) in their study reported that the average reduction percentage for BOD_5 was 50.61%, 46.38% for COD, 40.34% for nitrogen and 18.76% for phosphorus. Duckweed achieved efficiencies of 33.43% for BOD_5, 26.37% for COD, 17.59% for Nitrogen and 15.25% for Phosphorus while water lettuce attained removal efficiencies of 33.43% for BOD_5, 26.37% for COD, 17.59% for Nitrogen and 15.25% for Phosphorus.

Another study by Wahyudianto *et al*., (2019) showed that for *Equisetum hyemale* (horse tail reed) the TSS removal efficiency was between 34–93%. COD removal was between 74–95% and phosphate was between 29–90%. Given the high removal efficiency of horsetail reed for COD shown in the study, we used it in our study to ascertain its performance given the greywater characteristics.

The main mechanism for phosphorus removal in constructed wetland has been considered as adsorption and precipitation by a substratum surface containing free $Fe2^+$ and $Al3^+$ ions whereby phosphate displaces the hydroxyls from the Fe and Al hydrous oxides (Zhang, et al., 2015). Biological uptake by bacteria, phytoplankton and plants may also play a role whereas the possibility of phosphorus precipitation, adsorption of soluble phosphorus onto available surfacing cannot be ruled out (Weragoda, et al., 2012). It is worth noting that generally, constructed wetlands have low TP removal efficiencies. Zhang, et al., (2015) reported a 2005 review of phosphorus removal rates in HSSF CWs throughout the world whose results were an average mass-based efficiency of 32%. This was attributed to the fact that the uptake and storage of the soluble phosphorus is a reversible mechanism which allows for release of previously assimilated phosphorus once part of the root system (where 86–96% of the absorbed TP gets stored) dies and decays (García, et al., 2010).

The removal of total nitrogen in the constructed wetland mainly depends on microbial processes, such as nitrification and denitrification favoured by aerobic and anaerobic conditions respectively. It is also attributed to plant uptake and sorption (Rehman, et al., 2012). As the oxygen transport into horizontal sub-surface flow constructed wetlands is limited, enhanced nitrification cannot be expected. On the other hand, denitrification can be very efficient since the produced nitrate can be reduced by heterotrophic bacteria to nitrogen (Hoffmann, Platzer, Winker, & von Muench, 2011).

The literature indicates clearly that the performance of the constructed wetland is affected by various factors inclusive of macrophytes, substrates and nature of the wastewater.

2.4.3.3.3 Configuration of the wetlands

According to HABITAT (2008) constructed wetlands have various design configurations namely;

- Life form of the dominating macrophytes (free-floating, emergent, submerged),
- Flow pattern in the wetland systems (free water surface flow; subsurface flow: horizontal and vertical),
- Type of configurations of the wetland cells (hybrid systems, one-stage, multi-stage systems),
- Type of wastewater to be treated
- Treatment level of wastewater (primary, secondary or tertiary),
- Type of pre-treatment,
- Influent and effluent structures,
- Type of substrate (gravel, soil, sand, etc.)
- Type of loading (continuous or intermittent loading).

Nevertheless, the flow pattern is generally accepted as the basic criterion (Kayombo, *et al*., 2008). According to this criterion, constructed wetlands are classified into two basic types:

- Free water surface (FWS) constructed wetlands.
- Subsurface flow (SF) constructed wetlands.

According to Kadlec & Wallace (2009), free water surface constructed wetlands contain areas of open water, floating vegetation, and emergent plants while in sub-surface constructed wetlands, wastewater is intended to stay beneath the surface of the media and flows in and around the roots and rhizomes of the plants. Since the wastewater in subsurface constructed wetlands is not exposed during the treatment process, the risk associated with human or wildlife exposure to pathogenic organisms is minimized.

Subsurface flow treatment wetlands are subdivided into two categories; Horizontal Flow (HF) and Vertical Flow (VF) wetlands depending on the direction of water flow.

1) Horizontal Flow (HF)

It is called a HF wetland because the wastewater is fed in at the inlet and flows slowly through the porous substrate under the surface of the bed in a more or less horizontal path until it reaches the outlet zone (HABITAT, 2008).

2) Vertical Flow (VF)

Vertical flow constructed wetlands comprise a flat bed of sand/gravel topped with sand/gravel and vegetation. Wastewater is fed from the top and then gradually percolates down through the bed and is collected by a drainage network at the base (HABITAT, 2008).

2.4.3.3.4 Pollutant Removal Mechanisms

Wetlands have a higher rate of biological activity than most ecosystems and therefore can transform many of the common pollutants that occur in conventional wastewaters into harmless byproducts or essential nutrients that can be used for additional biological productivity (Kadlec & Wallace, 2009). Wastewater treatment within a constructed wetland occurs as wastewater passes through the wetland soil medium and plants (Mthembu, *et al*., 2013).

The different pollutant removal mechanisms are described in here below.

1. **Microbially mediated processes**

Many wetland reactions are microbially mediated, which means that they are the result of the activity of bacteria or other microorganisms (Kadlec & Wallace, 2009). The activity of these organisms leads to the breakdown of organic matter. Interactions between micro-organisms and contaminants lead to biodegradation. Micro-organisms play a major role in removal of contaminants by transforming and/or accumulating them and converting them into their own biomass (Mthembu, *et al.*, 2013). Attached and suspended microbial growth is responsible for the removal of soluble organic compounds, which are degraded biologically both aerobically (in presence of dissolved oxygen) as well as anaerobically (in absence of dissolved oxygen) (UN-HABITAT, 2008).

2. **Sedimentation**

Settleable and suspended solids that are not removed in the primary treatment are effectively removed in the wetland by sedimentation (UN-HABITAT, 2008). The particulate organic matter entering with the influent wastewater is retained mainly by physical processes such as sedimentation (Dotro, *et al*., 2017). Treatment wetlands are very effective in removing suspended solids associated with the inlet flow. One of the primary mechanisms is gravitationally driven particulate settling due to the slow-moving water in the wetland environment. Solids sink in water due to the density difference between the particle and water (Kadlec & Wallace, 2009).

3. **Sorption**

The sorption process is important for phosphorous and ammonia-nitrogen removal (Kadlec & Wallace, 2009). The sorption capacity of media is finite and once they are saturated little additional sorption may take place. Ammonium is a cation and is therefore readily sorbed onto media particles within treatment wetlands (Dotro, *et al*., 2017). According to Kadlec & Wallace (2009) sorption can be described as a two-step process that is;

- Phosphorus rapidly exchanges between the soil pore water and soil particles or mineral surfaces (adsorption).
- Phosphorus slowly penetrates into solid phases (absorption).

4. **Photodegradation**

Many microorganisms, including pathogenic bacteria and viruses, can be killed by ultraviolet radiation (Kadlec & Wallace, 2009). In a natural system, such as a pond or an open-water wetland, sunlight provides a source of ultraviolet (UV) radiation. The effectiveness of the radiation depends on water quality factors, such as optical absorbance and suspended solids content (Kadlec & Wallace, 2009).

5. **Plant uptake**

Plants take up the dissolved nutrients and other pollutants from the water, using them to produce additional plant biomass. The nutrients and pollutants then move through the plant body to underground storage organs when the plants senesce, being deposited in the bottom sediments through litter and peat accretion when the plants die (Kayombo, *et al*., 2008).

6. **Transpiration Flux**

In aquatic and wetland systems with fully saturated soils or free surface water, the meteorological energy budget requires the vaporization of an amount of water sufficient to balance solar radiation and convective losses. Some of this vaporization is from the water surface (evaporation); some is from the emergent plants (transpiration). Vertical flows of water in the upper soil horizon are also driven by plant water uptake to support transpiration (Kadlec & Wallace, 2009). The water that flows in the wetland to the plants to support the transpiration carries with it contaminant concentrations.

Table 2-3 shows the particular removal mechanisms within constructed wetlands that eliminate different pollutants in greywater. The table was adopted from Kayombo *et al*., (2008) and Mthembu *et al*., (2013).

Table 2-3: Summary of Pollutants and their various pollutant removal mechanisms

Pollutant	Removal Mechanism
Organic material	Biological Degradation (aerobic and anaerobic), sedimentation, microbial uptake
Suspended solids	Sedimentation, filtration
Nitrogen	Ammonification followed by microbial nitrification, de-nitrification, plant uptake, matrix sorption, ammonia volatilization
Phosphorous	Matrix sorption, plant uptake
Pathogens	Natural die-off, predation, UV irradiation, excretion of antibiotics from macrophytes
Metals	Adsorption and cation exchange, complexation, plant uptake, precipitation, microbial oxidation/reduction

2.4.3.3.5 Performance Efficiency of Constructed Wetlands

The removal efficiencies of CWs depend on the choice of the type of liquid inlet and outlet configurations, feed rate, applied loads, environmental conditions, type of substrate, and the plant species used (Saraiva, *et al*., 2018).

Constructed wetlands have been shown to successfully reduce organic material, nutrients and pathogens. Studies by Mustafa (2013) carried out to establish the treatment performance of a pilot-scale constructed wetland receiving domestic wastewater from laboratories of various university departments indicated average removal efficiencies of BOD_5 concentrations over the monitoring period as 50% with mean effluent BOD_5 concentration of 34 ± 15.5 mg/l. The system achieved a solids removal efficiency of 73%, a 40.6% reduction in ammonia-nitrogen and a reduction of 52% in ortho-phosphate concentration. Pre- and primary treatment is essential to prevent clogging and ensure efficient treatment by constructed wetlands (Tilley, Ulrich, & Luthi,2014).

Table 2-4: Removal Efficiencies for Biological Treatment Systems

Biological Treatment Systems	Removal efficiencies for different parameters				
	COD	BOD	TKN	AS	SS
Membrane Bioreactor	86%	94.9%	33.3%	85.7%	
Anaerobic Baffled Reactor	50%	77%			73.4%

2.5 Pilot Plant

The plant behind Africa hall receives greywater from the hall's kitchen and consists of an Anaerobic Baffled Reactor and a Constructed Wetland. The constructed wetland is planted with *Equisetum hyemale* (horse tail reed) in pumice, gravel and plastic as substrate media.

The wastewater concentrations of the effluent discharging from Africa Hall were previously tested and results were as shown in Table 2-5. The sample collection and subsequent lab analysis was a one-off excursion.

Table 2-5: Quality characterisation of greywater from Africa hall kitchen

Parameter	Unit	Result
Biochemical Oxygen Demand	mg/l	881
Chemical Oxygen Demand	mg/l	1980
pH	-	6.76
Conductivity	µS/cm	1167
Turbidity	FAU	485
Total Suspended Solids	mg/l	956
Total Dissolved Solids	mg/l	1834
Total Phosphorous	mg/l	8.664
Total Nitrogen(Nitrate)	mg/l	25.5

As seen in Table 2-5, the greywater from Africa hall has a COD concentration greater than 1000mg/l. With such high concentrations, an anaerobic process is more efficient in pre-treatment of the wastewater stream even at fluctuating hydraulic loading rates (Anijiofor, *et al*., 2017). In particular, the anaerobic treatment system chosen was the Anaerobic Baffled Reactor which was designed to achieve a 50% removal efficiency for the different pollutant parameters in reference to the design approach discussed by Tayler (2018).

The key design parameters of the treatment plant are presented in Table 2-6 and Table 2-7.

Table 2-6: Design parameters of ABR

Settler compartment	Length	2.7m
	Width	1.3m
	Height	1.5m
Up flow compartments	Number	3
	Length	0.8m
	Width	1.3m
	Height	1.5m
	Hydraulic Retention time	36 hrs
Influent Parameters	Peak daily flow rate	2.88m^3/d
	Design influent COD Concentration	1980mg/l

Table 2-7: Design parameters of the CW

Parameter	Value
Depth(m)	0.5m
Area(m^2)	18
Hydraulic Retention time (days)	2.88
Design flow rate	1.056m^3/d
Design Influent BOD_5 concentration	441mg/l

2.5.1 Anaerobic Baffled Reactor

The anaerobic baffled reactor was designed as a pre-treatment system due to its efficient removal of organic matter and suspended solids prior to treatment in the constructed wetland. The greywater flows into the ABR settler compartment by gravitational force through an inlet pipe that directs the waste liquid directly to the bottom of the given compartment. The purpose of this sort of flow design is to deter unnecessary turbulence in any of the compartments (Dahlan, Hassan, & Zwain, 2013). The settler compartment serves to separate large solids ahead of the baffled sections (Tayler, 2018). The settler's large plan area, as seen in Figure 2-3, enables it to attenuate the peak flows so as to reduce on the hydraulic load variations on the subsequent up-flow compartments (Tayler, 2018).

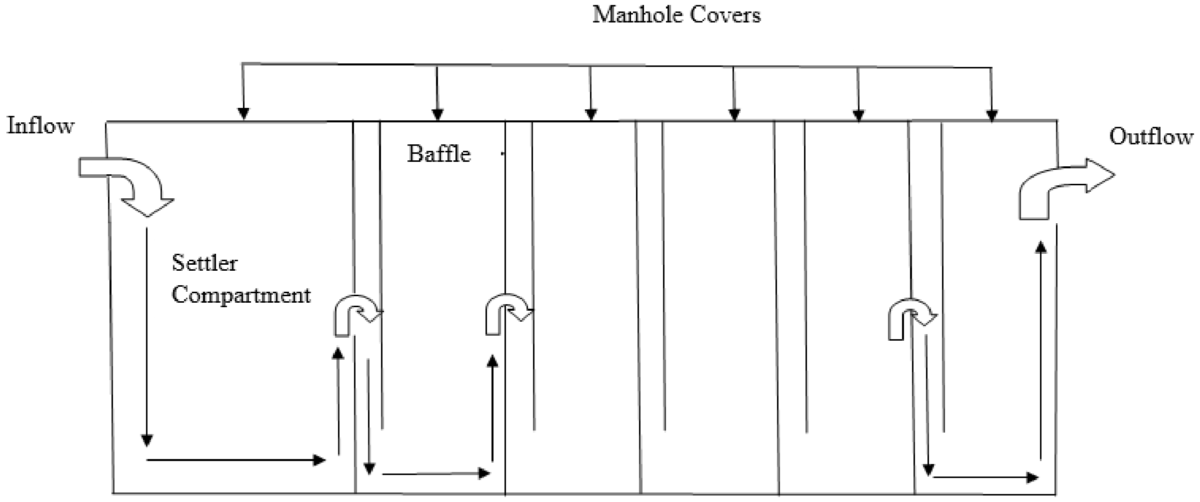

Figure 2-3: Anaerobic Baffled Reactor Layout

Due to the anaerobic conditions, a granulated sludge blanket, through which the wastewater must pass as it flows upwards, is formed (Dahlan, Hassan, & Zwain, 2013). The solids in the wastewater are trapped in the sludge blanket from where anaerobic bacteria consume the organics as food. An anaerobic process is a process where organic matter in wastewater is converted to methane and carbon dioxide through a series of reactions involving a consortium of obligate and facultative anaerobic microorganisms (Dahlan, Hassan, & Zwain, 2013). As wastewater builds up, the carryover water starts to overflow to the next compartment. The partially clarified effluent undergoes the same action in each subsequent compartment until the outlet pipe. An anaerobic filter is installed in the last compartment of the ABR to further improve its treatment performance. The configuration of the ABR is such that there is a 70% reduction in the suspended and organic matter of the wastewater (Dahlan, Hassan, & Zwain, 2013). This is achieved by the intense contact time of the wastewater with the active biomass at the bottom of the reactor.

Despite some variations in the design of different ABRs, the operational concept remains the same. Some designers use transfer openings in the baffle walls to direct the flow from one compartment to the next. Others use pipes that accumulate the effluent from the top of one compartment and deliver it to the bottom of the next compartment (Figure 2.3). To avoid short circuiting, however, the pipe or transfer openings must be set level. One of the advantages of using this system is that it requires low level of maintenance due to absence of mechanical moving parts and the baffle positions are already fixed without needing further adjustment. Maintenance is limited to the removal of accumulated sludge and scum every 1 to 3 years (Tilley, Ulrich, & Luthi, 2014).

2.5.1.1 Treatment mechanisms in the ABR

The wastewater treatment properties of the ABR are governed by two main processes namely; anaerobic digestion and solid retention.

Overtime, after a given start-up period, the cumulative deposition of the wastewater solids culminates into active microbial mass which feeds on organic pollutants in the wastewater in the absence oxygen (Anaerobic digestion). Solid retention takes place through the entrapment of solids in the sludge blankets of the settler and up-flow compartments.

During anaerobic digestion, organic matter is converted to carbon dioxide (CO_2) and methane (CH_4) in a series of interrelated biochemical processes (Reynaud, 2014). These include; hydrolysis, acidogenesis, acetogenesis and methanogenesis. These processes are facilitated by a consortium of different anaerobic micro-organisms (Dahlan, Hassan, & Zwain, 2013).

During hydrolysis, complex organic polymers, such as carbohydrates, proteins and lipids are broken down by hydrolytic micro-organisms to simple sugars, amino acids and long chain fatty acids. Acidogenesis refers to the fermentation of these simple sugars and amino acids to simple organic acids. The acetogenic micro-organisms further degrade the simple organic acids to acetic acid during the so called acetogenesis. During the last step, the methanogenesis, methane is either produced by the slow-growing hydrogenotrophic methanogens which use or by a group of archea called acetoclastic methanogens which converts acetic acid under strictly anaerobic conditions to methane (Reynaud, 2014).

2.5.2 Constructed Wetland

Artificially constructed ponds and wetlands have a growing popularity due to the fact that they offer relatively passive, low maintenance and operationally simple treatment solutions while potentially enhancing habitat, recreational, and aesthetic values within the urban landscape (Headley and Tanner, 2012).

The constructed wetland considered in this study was designed as a plug flow reactor using the P-K-C* approach stated in Kadlec & Wallace (2009). The P-K-C* approach was considered for design of the constructed wetland using the BOD_5 and COD values of the greywater which were above the NEMA effluent discharge standards and were considerably highest among other parameters. In the P-K-C* equation a target effluent value of 18mg/l of BOD_5 corresponding to 95% removal efficiency was designed for.

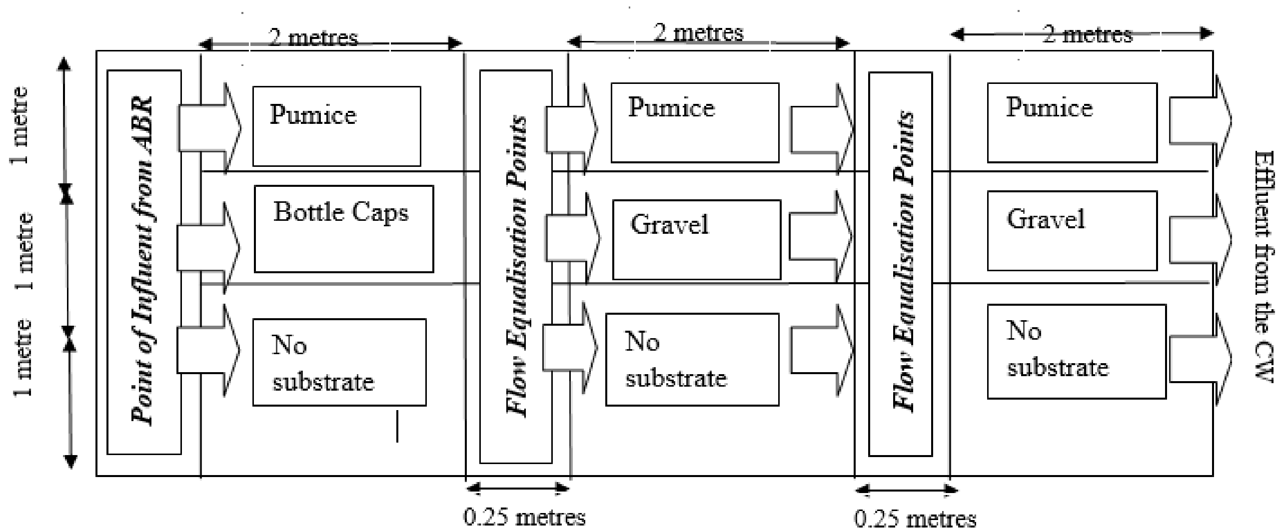

Figure 2-4: Constructed Wetland layout

The wastewater from Africa Hall was characterized by a BOD_5 concentration of 881mg/l from the preliminary tests which results into a cross section organic loading of $141gBOD_5/m^2.d$. Following the maximum cross sectional organic loading rate of 100g $BOD_5/m^2.d$ for constructed wetlands as recommended by Wallace (2014) and Chazarenc, *et al*., (2007), the installation of a pre-treatment system before the wastewater is directed to the constructed wetland is warranted. This is to reduce on the cross sectional organic loading of the constructed wetland to prevent hydraulic dysfunctions via internal clogging.

2.5.2.1 Substrates used at the Pilot Plant

1. **Floating mat (represented as No substrate in Figure 2-4)**

The emergent macrophyte (horsetail reed) was planted on a Styrofoam mat floating on the surface of the water. The roots of the macrophyte are not embedded in any media but rather hang beneath the mat but within the water. The plant stems remain above the floating Styrofoam mat and are exposed to the atmosphere. In this way, the plants grow in a hydroponic manner, taking their nutrition directly from the water column in the absence of soil or any other media (Headley and Tanner, 2012).

The floating mat, to avoid wind sweep, must be constrained against lateral movement. At the pilot plant, this was done by using Styrofoam boards which were big enough to just fit in the cells in which they were placed. According to Chen *et al*. (2016), floating mats are effective in the removal of suspended solids due to the laminar conditions in the open water layer between the root mat and the water body column where turbulence and re-suspension of particles are minimized. The roots also provide a large surface area for biofilm attachment which carries out treatment of the greywater by removal of organic matter. In the same study, Chen *et al*. (2016), the following removal efficiencies for different contaminant parameters were reported; chemical oxygen demand (COD) and biochemical oxygen demand (BOD_5) removal efficiency varied from 17 to 84 % and 36 to 90 %, respectively. TN load removal rates ranged from 0.13 to 10.64 $g/m^2/day$ with removal efficiencies of 3–92 %. For TP, a load removal rate retention of 0.08 to 7.47 $g/m^2/day$ with removal efficiencies of 5 to 88 % were reported.

2. **Plastic**

According to Dallas & Ho (2005), macrophyte plants must be able to penetrate the media in which they are planted for their structural support. To this end, relatively soft plastic (PET bottle covers) was selected for use in the one of the beds of the constructed wetland. According to Rehman, *et al*.,(2012), plastic media allows for good microbial growth due to high specific surface area and low molecular weight. This aids in the removal of organic matter from the greywater. A study reported by Dallas & Ho (2005) posits that plastic as a substrate media achieved removal rates of 99.9% for faecal coliforms in both dry and wet seasons. The superior performance was attributed to the greater retention times and increased root mass achieved by the macrophyte in the media. In addition, it had greater than 87% removal of BOD under both dry and wet seasons.

3. **Pumice**

A study by Njau, Minja, & Katima (2003) reported that the high specific surface area of the pumice rock avails an enhanced area not only for adsorption processes of particulate pollutants and solids but also for microbial attachment. Ideally, this enhances the removal efficiencies of the pumice in the removal of particulate phosphates, suspended solids and organic matter. Another study by Çifçi & Meriç (2015), posits that the skeleton structure of the pumice rock allows for movement of water and ions into and out of the crystal structure through open channels. This favours sorption of the soluble pollutants as well.

Al Kholif & Jumali (2017) reported a BOD_5 removal efficiency for pumice ranging from 78 – 98% in the treatment of greywater which varied depending on the source of the greywater.

2.6 Greywater Reuse

The acceptability of recycled water for any particular end use is dependent on its physical, chemical and microbiological quality. The standards to be considered regarding greywater reuse are dependent on the activity in which the treated greywater is to be used. Greywater can be put to a number of uses such as toilet flushing, irrigation, construction and occasionally groundwater recharge. The most paramount consideration that cuts across all these uses is public health protection, and thus all water recycling standards include at least one of the parameters relating to the potential for disease transmission such as FC, TC and BOD_5. However, the incidence of disease is dependent upon more than just the concentration of organisms. It also depends on variations in population size, dose response, exposure and time elapsed between generation and application of greywater. Table 2-8 shows the risk allocation of greywater reuse depending on these different factors that influence disease incidence (Imhof & Muhlemann, 2005).

Table 2-8: Risk allocation of greywater reuse

	Lower risk	Intermediate risk	Higher risk
Population	Small population (single family)		Large population (multi-occupancy)
Exposure	No body contact (Sub-surface irrigation)	Some contact (WC flushing, bathing)	Ingestion (drinking)
Dose-response	Less than 1 virus/bacteria per sample	-	Greater than 1 virus per sample Greater than 10^6 bacteria per sample
Delay before reuse	Immediate reuse	Reused within hours	Reused within days

For developing countries, it is more feasible to rely on the WHO guidelines for their own legislation than on the following USEPA guidelines as they are unjustifiably strict on microbial standards for wastewater irrigation (Imhof & Muhlemann, 2005). Unfortunately, the non-restricted and restricted guidelines for greywater application in agricultural irrigation released in 2006 by the World Health Organization (WHO) pay more attention to microbial parameters than on physical and chemical ones (Vuppaladadiyam, et al., 2018). For this reason, other guidelines were sought in order to assess the feasibility of the treated greywater for reuse in this study based on the physical and chemical parameters. Such guidelines include those from the Food and Agriculture Organisation (1994), United States Environmental Protection Agency (2004) and the Central Pollution Control Board (2012). The guidelines from FAO, however, do not necessarily refer to reclaimed greywater but signify the limits within which the health of crops and soils can be safeguarded and so should also be met by the greywater used for irrigation.

CHAPTER 3 - METHODS AND MATERIALS

3.1 Introduction

This section focuses on the steps taken to achieve the specific objectives presented in Section 1.3 (Chapter 1). The chapter presents the data/sample collection techniques employed as well as the guidelines followed in testing and analysing the samples.

3.2 Characterisation of the Greywater

3.2.1 Flow measurements

The flow rate of the greywater from Africa hall was measured so as to ascertain the greywater hydraulic load on the treatment system. These measurements for the greywater from the Africa Hall kitchen were carried out using a bucket of known volume (20 litres) which was appropriately placed at the kitchen outlet pipe to collect greywater flows for thirty-minute intervals over a 2-hour period (10:30 am – 12:30 pm).

Figure 3-1: Collection of raw greywater from the Africa hall kitchen

The procedure was repeated for the effluent from the ABR and the one from the constructed wetland.

Figure 3-2: Collection of greywater from the constructed wetland outlets

This procedure was undertaken once a week, on the day the water samples were being collected (Wednesday) from which February 2020 to March 2020 and thereafter from November 2020 to December 2020. The disconnect between sampling periods happened due to the COVID-19 pandemic that had us under lockdown for most of the year. Quantifying how much water was collected in the two-hour period allowed us to calculate the flow rate of the raw greywater from the kitchen, that of the pre-treated greywater from the ABR as well as such that of the treated greywater from the constructed wetland on any given sampling day.

3.2.2 Water Quality Parameters

In order to obtain influent and effluent quality characterisations for both the ABR and CW, laboratory tests were carried out for the greywater from Africa hall, effluent from the ABR and effluent from all three rows of the CW.

3.2.2.1 Sampling

In order to assess the performance of the ABR and CW in treatment of kitchen greywater with respect to the different pollutants, the influent into and effluent out of each treatment system was characterised. The parameters analysed for were physical (colour, suspended solids, dissolved solids, turbidity, pH and fats, oils and grease), chemical (COD, BOD_5, alkalinity, total nitrogen, total phosphorus) and Microbiological (faecal coliforms).

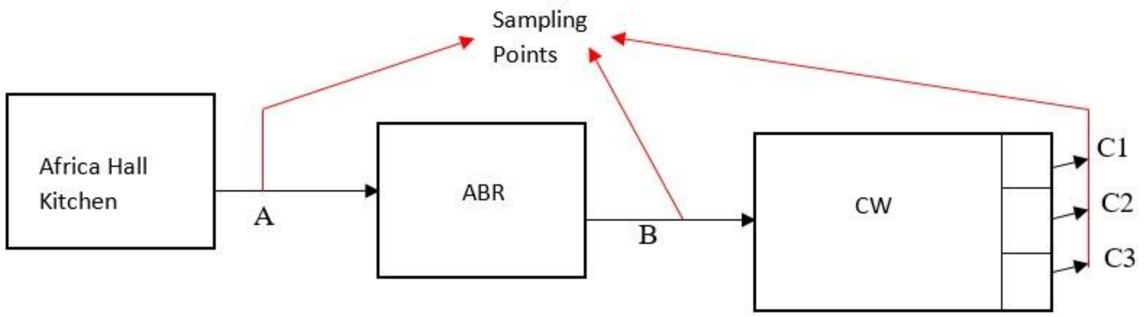

Figure 3-1: Sampling points along the treatment system

Samples of untreated and treated wastewater were collected from the Africa hall kitchen and effluent of the ABR and CW respectively from the sampling points shown in Figure 3-1. The sampling excursions were done during the same periods for flow measurements as described in section 3.2.1. The samples were collected in thoroughly washed sampling bottles and put in a cooling box to be transported to the lab for analysis.

3.2.3 Laboratory analysis

The BOD_5 as described in section 4.3.2 is an indirect measurement of organic matter in wastewater. The BOD_5 was measured at the Times Analytics laboratory in Kitintale using the dilution method, 5-day BOD test (APHA, AWWA & WEF, 2017). The COD was determined by the open reflux method (APHA, AWWA & WEF, 2017) using a COD reactor (Camlab Hach) at Times Analytics laboratory in Kitintale.

The total solids, suspended solids and dissolved solids parameters give an indication of the quantity of solids present in wastewater and the nature that is; whether dissolved or suspended (American Public Health Association; American Water Works Association; Water Environment Federation;, 2017). A mermert oven in the Public Health and Environmental Engineering lab at Makerere University was used to dry the samples at 105ºC and 180ºC for the TDS. This was done in reference to the method Total Solids Dried at 103°C -105°C and Total Dissolved Solids Dried at 180°C (APHA, AWWA & WEF, 2017). The total suspended solids was the difference between the total solids and the total dissolved solids.

The faecal coliform test was conducted using the Membrane lauryl Sulphate Broth (MLSB) method in reference to (APHA, AWWA & WEF, 2017). The medium with the greywater was autoclaved for 24 hours at 121 °C.

The turbidity and apparent colour were determined by the absorptometric method and platinum cobalt method respectively (APHA, AWWA & WEF, 2017). Readings were taken from a colorimeter, Hach DR/890. The turbidity readings was programmed to.. and apparent colour to.. The pH was determined using the Hach HQ 30d flexi pH meter

For the case of Total phosphorous and Total Nitrogen, persulphate digestion method was used in reference to (OKalebo, Gathua, & Woomer, 2002). The readings for total phosphorous and total nitrogen were read using the colorimeter Hach D/890 after digesting. The total alkalinity was determined using the titration method (APHA, AWWA & WEF, 2017). Readings for the total alkalinity were determined using a Hach digital titrator.

Fats, oil and grease (FOG) are a key parameter in monitoring raw greywater streams and the efficiency of pre-treatment systems in separating the FOG. The latter was determined according to the Trichlorotrifluoroethane-soluble floatable oil and grease method (APHA, AWWA & WEF, 2017). All the samples were analysed in the laboratory within 24 hours after collection from the field.

3.2.3.1 Data analysis

The pollutant concentrations obtained from lab analyses of the samples collected from the ABR and CW were multiplied by their corresponding flows to transform them into pollutant loads as shown in Equation 3-1.

$$Pollutant\ Load = Pollutant\ Concentration \times Flows$$

Equation 3-1: Calculation of pollutant loads

Using Equation 3-2, the removal efficiencies per pollutant for the ABR and CW units were calculated. Pollutant loads, and not concentrations were used for this calculation situation because they provide for a more accurate picture of the reductions that actually happen. Take the constructed wetland for example, due to its exposure, it experiences water losses due to evaporation and evapotranspiration. If water is simply lost to the atmosphere, this lost water is pure (void of the constituent), and the constituents in the effluent thus become more concentrated by simple water loss. This results in an apparent reduction in the actual removal that took place in the unit.

$$\frac{Influent\ load - Effluent\ load}{Influent\ load} \times 100\%$$

Equation 3-2: Calculation of removal efficiency using pollutant load

In order to determine the statistical difference (p-values) between the ABR influent and effluent as well as that between the removal efficiencies of the three different CW media, the following parametric statistical tests were carried out; t-test and ANOVA (One way) respectively. These computations were all done using Microsoft Excel 2019 under the premise of a 95% confidence interval.

By calculating the mean of efficiencies, we obtained the average removal efficiency of each treatment system that is; ABR, horsetail reed floating mat, plastic and pumice. The statistical significance of the differences between the removal efficiencies of the CW media was used to determine which media performed better than the other in the removal of a given pollutant.

The average values of the pollutant concentrations of the effluent from the CW were compared with the national effluent discharge standards to ascertain whether the effluent is safe for discharge into the environment.

3.3 Girth measurement

The constructed wetland is planted with horsetail reed in three different columns. Two columns have pumice and plastic as the substrate in which the macrophyte is planted while the third does not have any substrate and therefore acts as a control. Each column is divided into three cells which are meant to function as intermediate monitoring points. Each cell has six horsetail reed plants as indicated in Figure 3-3.

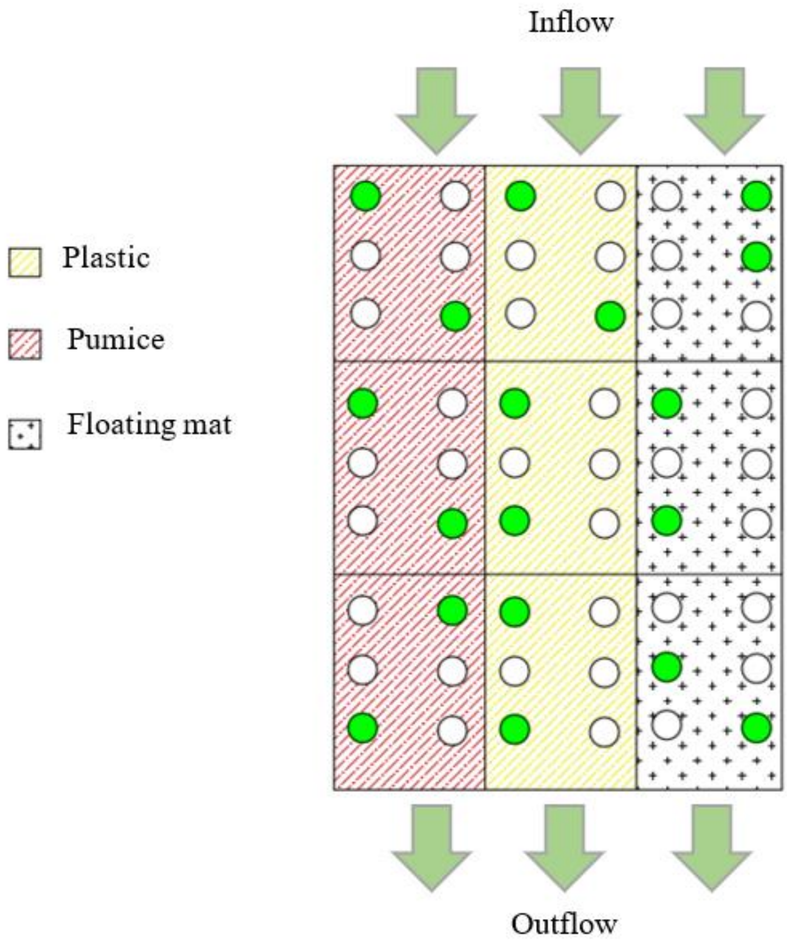

Figure 3-3: Selected horsetail reed plants for girth measurement shown as green circles

It was deemed important to measure the macrophyte's growth rate as it spoke to the nutrient uptake from the greywater being treated. To measure the growth rates of the macrophyte, the girth of shoots of the selected plants was to be measured over a period of eight weeks. The selection of the shoots to monitor was premised on the following:

a) Two of the sturdiest plants in each cell were chosen.
b) Two relatively young shoots of horsetail reed were selected from each of the plants selected in (a) above and marked using tape. The marking was done at relatively the same distance above the horizontal.

A string was wrapped around the marked areas of each of the selected shoots, tight enough to get an accurate measurement of the shoot's circumference but loose enough not to damage the plant. The string was then transferred to a steel tape where the girth measurement was read off in inches.

3.4 Calculation of overall efficiency

Given the construction of the treatment plant, the greywater followed three different treatment trains, each arranged in series, that is; from the ABR through the horsetail reed floating mat CW unit, from the ABR through the CW unit with plastic as the substrate and also from the ABR through the CW unit with pumice as the substrate. The overall treatment efficiency (pollutant removal efficiency) for each of these treatment trains was calculated using Equation 3-3 as adapted from von Sperling, Verbyla, & Oliveira, (2020).

$$Eoverall\ (\%)\ = 100 \times 1 - \left(\left[1 - \frac{E1}{100}\right] \times \left[1 - \frac{E2}{100}\right] \right)$$

Where E1 – Removal efficiency of a particular pollutant in the ABR

E2 – Removal efficiency of a particular pollutant in a given CW unit

Equation 3-3: Calculation of Overall efficiency

3.5 Study limitations

This study was not without limitations. Some of these include;

1. The untimely occurrence of the COVID-19 pandemic. As mentioned in Section 3.2.1, the pandemic had us under lockdown from March 2020 to October 2020. This affected the monitoring of the macrophyte girth growth since the plant continued to grow without us carrying out the much-needed measurements. However, post lockdown, we measured twelve of what we determined to be sturdy shoots from the plants that had been selected pre-lockdown in order to get the gain in girth as we had anticipated. We compared these new twelve girths with twelve of the “biggest” pre-lockdown girths in order to discuss the macrophyte growth in Section 4.3.2.7.

CHAPTER 4 - RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results and their discussion.

4.2 Grey water characteristics

The average and ranges of various pollutant concentrations of the raw greywater flowing from Africa Hall kitchen are shown in Table 4-1 where they are compared with the national discharge standards.

Table 4-1: Pollutant composition of raw greywater

PARAMETERS	CONCENTRATIONS (mg/l)		Maximum Permissible Concentration (NEMA)*
	Average	Range	
Temperature (°C)	23.93±1.17	21.436 - 25.4	**20 – 350 °C**
pH	5.52±0.38	4.7932 - 6.12	**6.0 – 8.0**
Turbidity (FAU/NTU)	232.87±89.25	160.08 - 388	**300**
Alkalinity	81.91±86.22	19.78 - 298.92	
Apparent Color (Pt-Co)	1330.3±501.81	144 - 1760	**300**
TSS	614.82±719.02	75.44 - 2142	**100**
TDS	724.3±237.62	432.4 - 1200	**1200**
TS	1339.12±869.15	507.84 - 2844	
TP	5.93±2.56	2.27608 - 9.892	**10**
FOG	45.93±40.28	14.72 - 120	**10**
TN	45.32±20.01	17.5 - 90	**10**
COD	976.16±566.92	167.44 - 1724.32	**100**
BOD	705.5±546.61	90.16 - 1540	**50**
FC (cfu/100ml)	12294.35±10819.39	2944 - 31300	

[Mean values ± Standard deviations, n=8]

Evidently, to a larger extent, the pollutant concentrations of the raw greywater are above the maximum permissible concentrations for disposal. With that, it becomes imperative that this greywater be treated before being disposed into the environment.

4.2.1 pH and temperature

From Table 4-1, it can be observed that the greywater mean temperature was 23.93±1.17ºC ranging from 21.44 ºC to 25.4 ºC which is in line with that reported in previous studies. Katukiza., *et al* (2015) reported temperatures in a range of 19-29° C for household greywater in sample Ugandan peri-urban areas. Morel & Diener (2006) notes that the temperature of greywater is often higher than that of the water supply and varies within a range of 18-30°C due to the activities in the kitchen like cooking which utilize warm water. The pH of the greywater from the kitchen is 5.61±0.3 which is less than the stipulated national discharge standards.

4.2.2 Turbidity and Colour

The turbidity of the greywater was a range of 160 NTU to 388 NTU with a mean value of 232.87±89.25 NTU. The high turbidity is attributed to left-over food and soil particles from kitchen sinks (Morel & Diener, 2006).

The grey water exhibited apparent colour levels with an average of 1330.3±501.81 Pt-Co and range of 144 Pt-Co to 1760 Pt-Co. Apparent colour in greywater can be attributed to the presence of soil matter and dyes from washing of foods in the kitchen (Ansah *et al*., 2011).

4.2.3 Solids

The greywater from the kitchen had on average, 614.82±719.02 mg/l of Total Suspended Solids with a range from 75.44 to 2142 mg/l, 724.3±237.62 mg/l of Total Dissolved Solids with a range from 432.4 to 1200mg/l and 1339.12±869.15 of Total Solids with a range from 507.84 - 2844mg/l. The value of suspended solids measured was much lower than that from a study reported by (Niwagaba, et al., 2014) where average values of 5,176 mg/l were observed. This may be due to the presence of an equalisation tank where sedimentation takes place prior to entering the ABR.

4.2.4 Nutrients

The total phosphorous measured in the greywater from the Kitchen was with mean value of 5.93±2.56 mg/l with levels ranging from 2.27608 - 9.892mg/l. The phosphorous in kitchen greywater according to Morel & Diener (2006) is attributed to the dishwashing detergents. The value recorded in this study is similar to that reported by Imhof & Muhlemann (2005) in a study on greywater in developing countries which was 3.1mg/l to 10 mg/l.

The total nitrogen concentrations for the greywater discharged from the kitchen ranged from 17.5 – 90 mg/l with an average value of 45.32±20.01mg/l. This value is quite similar to those in literature with ranges of 4-74 mg/l denoted for kitchen greywater by Boyjoo , Pareek , & Ang (2013) who attribute it to the waste in kitchen water. The presence of nitrogen in greywater is attributed to the presence of ammonia containing cleansing products and proteins in meats and vegetables by Morel & Diener (2006).

4.2.5 BOD_5 and COD

The greywater exhibited BOD_5 concentrations ranging from 90.16 - 1540 mg/l with a mean value of 705.5±546.61mg/l. The measured COD ranged from 167.44 - 1724.32 mg/l with an average concentration of 976.16±566.92 mg/l. The COD concentrations are within the ranges 50-2,568 mg/l for dark greywater and 55-633 mg/l reported by Albalawneh & Chang (2015).

The greywater is with a COD/BOD_5 ratio less than 2 (1.32) which indicates that it is with a comparably low content of non-biodegradable COD in the wastewater according to Achour (2016). Conversely, there is, therefore, high content of biodegragbale COD whose removal is favored by the biological processes within the anaerobic baffled reactor. This is deliberated upon further in Section 4.3.1.

4.2.6 FOG

The FOG values for the greywater discharged from the kitchen ranged from 14.72 - 120 mg/l with an average concentration of 45.93±40.28mg/l. The greywater discharged presents values similar to those Abdel- Shafy et al (2015) who reported an average concentration of 118.5mg/l for FOG of greywater in Egypt. FOG can be caused by matter such as food scraps, meat, cooking oil and butter (Husain, et al., 2014).

4.2.7 Faecal Coliforms

The faecal coliforms in the kitchen greywater averaged at 12294.35±10819.39 cfu/100ml within a range of 2944 - 31300 cfu/100ml.

4.3 Performance of the treatment plant

The averages, standard deviations and ranges of different pollutant concentrations for the effluent of the different treatment units over eight weeks are shown in Table 4-2.

Table 4-2: Pollutant concentrations and ranges for treated effluent from the ABR and CW units

Parameter	ABR		Floating Mat		Plastic		Pumice	
	Concentration	**Range**	**Concentration**	**Range**	**Concentration**	**Range**	**Concentration**	**Range**
Temperature (°C)	23.78±1.24	21.068-25.3	23.53±1.23	21.068-25.1	23.42±1.24	20.976-25.1	23.49±1.3	20.792-25.1
pH	6.85±0.45	5.9064-7.38	7.05±0.61	5.7868-7.59	6.92±0.72	5.4832-7.59	6.97±0.65	5.6396-7.57
Turbidity (FAU/NTU)	57.88±34.76	26.32-125	17.38±10.97	4.6-32	15.06±7.49	6-27	17.51±15.24	5.64-47
Alkalinity	299.96±161.41	97.76-533.92	260.32±173.12	50.9036-537.68	264.95±196.13	57.6564-584.96	251.28±175.63	60.26-567.76
Apparent Color (Pt-Co)	415.87±251.43	214-910	164.82±88.5	92-323	137.15±91.72	34.04-286	270.6±180.48	76.36-539
TSS (mg/l)	31.79±31.83	0-106	3.1±3.32	0-9	24.68±46.33	0-146	31.6±54.31	0-168
TDS (mg/l)	620.54±199.77	280-994	539.31±246.12	370-1100	470.65±219.2	271.68-856	477.05±154.96	354.24-778
TS (mg/l)	473.98±346.17	0-1094	526.3±253.62	364-1106	486.21±257	286.08-1002	499.05±209.13	359.04-946
TP (mg/l)	8.11±3.13	3.786-11.756	2.92±2.57	0.86112-8.274	2.81±3.12	0.06072-8.112	4.17±2.46	2-8.262
FOG	10.11±6.15	3-19	13.65±8.83	4-32	13.61±11.28	0-32	9.57±7.92	0-22
TN (mg/l)	66.72±43.9	6.3-130	37.67±37.73	3.84-100	28.61±43.97	0-130	16.56±22.98	0-60
COD (mg/l)	56.46±19.16	31.28-97.533	30.05±11.16	13.8-49.18	38.65±58.55	11.786-193.27	24.96±11.49	11.04-45.311
BOD (mg/l)	94.52±166.66	8.28-530.24	18.79±12.89	0.92-38.04	19.89±32.3	2.76-104.71	15.69±13.26	0-40.55
FC(cfu/100ml)	9070.69±8415.07	2237.44-23788	3084.03±2861.13	760.7296-8087.92	3628.28±3366.03	894.976-9515.2	1995.55±1851.32	492.2368-5233.36

[Average values ± Standard deviations, n=8]

4.3.1 Treatment performance of Anaerobic Baffled Reactor

The anaerobic baffled reactor (ABR) is a competitive alternative to traditional anaerobic reactors because its unique construction provides numerous advantages including better resilience to hydraulic and organic shock loadings, longer biomass retention times, lower sludge yields, and the ability to partially separate the various phases of anaerobic catabolism (Barber & Stuckey, 2000). It is therefore of little wonder that it achieved positive removal efficiencies for all the greywater pollutants for which we tested. This indicates the presence of different but coherent treatment mechanisms in the ABR compartments.

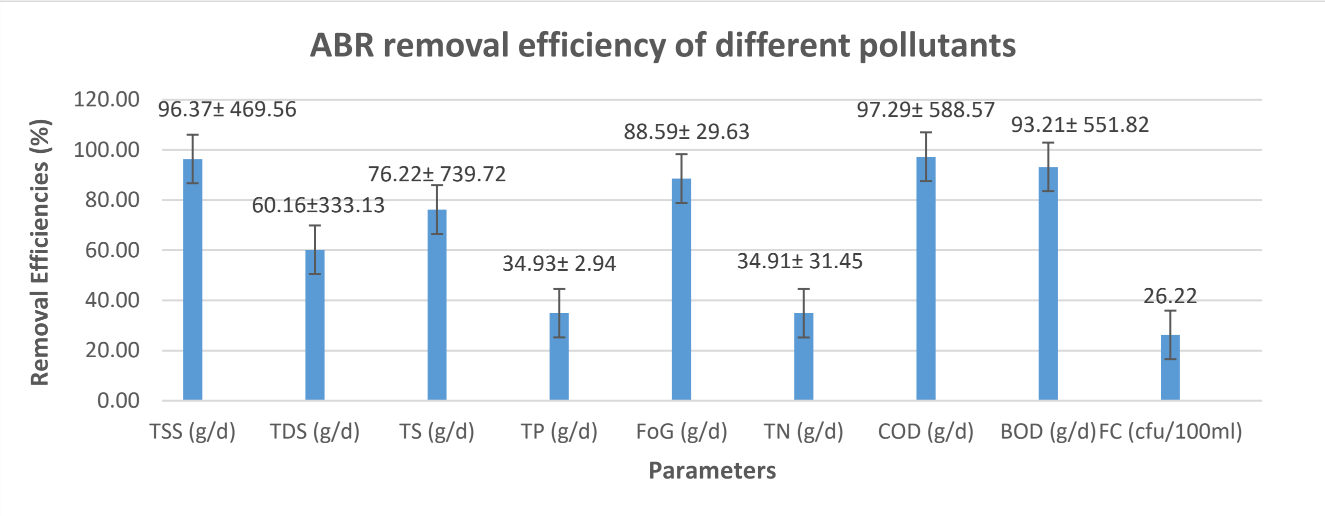

Figure 4-1: ABR average removal efficiencies

[Average values ± Standard deviations, n = 8]

4.3.1.1 BOD_5 and COD

As seen in Figure 4-1, the system achieved an average 93.21±551.82% BOD_5 and 97.29±588.57% COD removal efficiency.

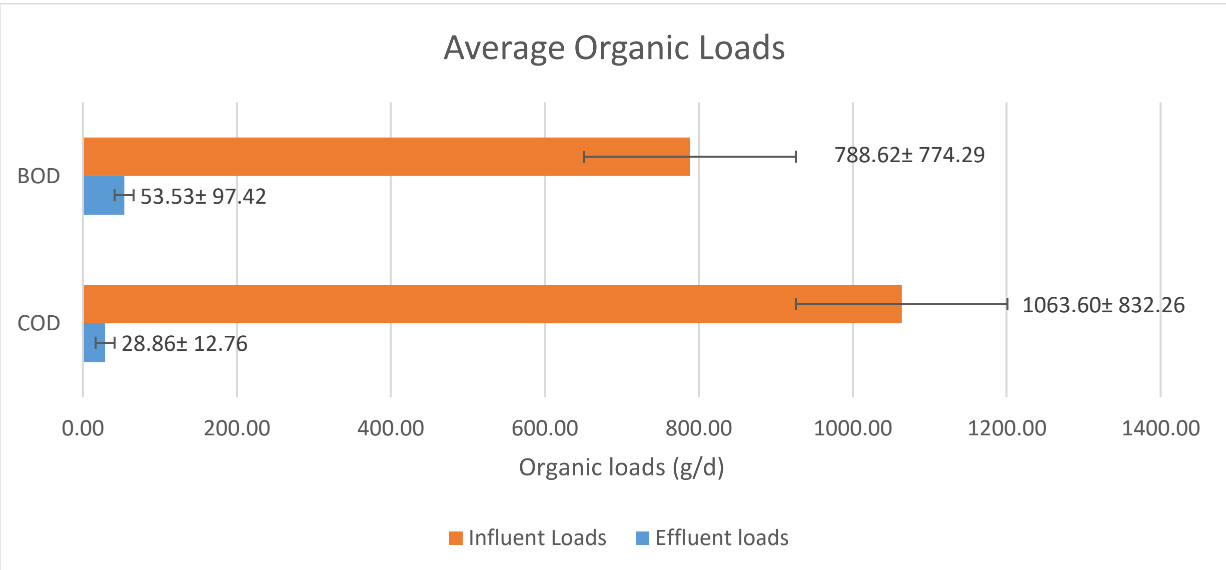

Figure 4-2: Average loads of Organic content in ABR influent and effluent

[Average values ± Standard deviations, n=8]

The high removal efficiency of BOD_5 can be attributed to the intimate contact the water has with the active biomass at the bottom of each compartment. The latter degrade the organics within the greywater by way of anaerobic digestion.

Following calculations of the COD/BOD_5 ratio of the ABR influent, it was concluded that the influent was readily biodegradable (COD/BOD_5 ratio <2) which indicates a comparably low content of non-biodegradable COD in the wastewater. Reynaud (2014) argues that anaerobic processes can only remove the biodegradable fraction of the COD to produce non-biodegradable COD. We therefore attribute the high COD removal efficiency to readily available bio-degradability of the water and the effective anaerobic processes in the ABR.

The average COD concentration of the ABR effluent as seen in Table 4-2 (56.46±19.16 mg/l) is similar to that reported by Foxon, *et al*., (2004) whose ABR attained 82.1 ± 16.0 mg/l in the treatment of domestic wastewater from sample homes in Durban, South Africa.

4.3.1.2 Solids

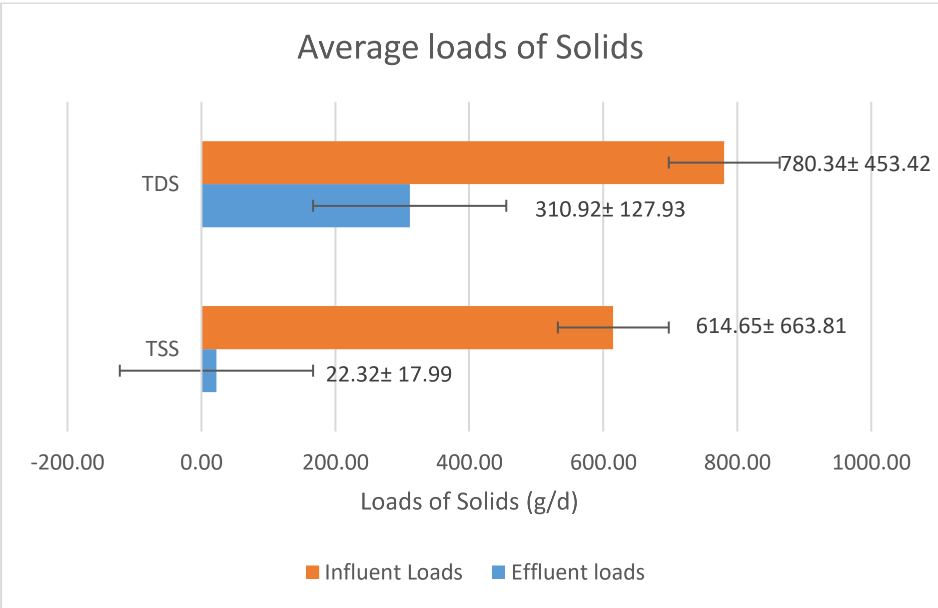

Figure 4-3: Average loads of Solids in the ABR influent and effluent

[Average values ± Standard deviations, n=8]

- **Total Suspended Solids**

  The suspended solids removal averaged at 96.37± 469.56 %. The retention of solids can be attributed to the up-flow pattern followed by the wastewater as it goes through the compartments. As the water goes up and over from one compartment to another, some of the flocculated suspended particles, unable to counter gravity trickle down to the bottom of a compartment. The ABR is also designed with a settler compartment which serves to separate large solids (Tayler, 2019). These sedimentation processes also allow for retention of particulate organic matter within the system as settled sludge, which contributes to the overall reduction in BOD_5 and COD. However, some of the suspended solids get trapped in the compartment's sludge blanket as the water flows from one partition to another.

- **Total Dissolved Solids (TDS)**

  The ABR achieved an average removal efficiency of 60.16±333.13% for TDS having reduced the dissolved solids from 780.34± 453.42 g/d in the influent to 310.92± 127.93 g/d in the effluent. TDS is a combination of organic and inorganic but dissolved solids. The removal efficiency can be attributed to the degradation of the largely organic dissolved solids by the active biomass at the bottom of the ABR compartments.

4.3.1.3 Nutrients

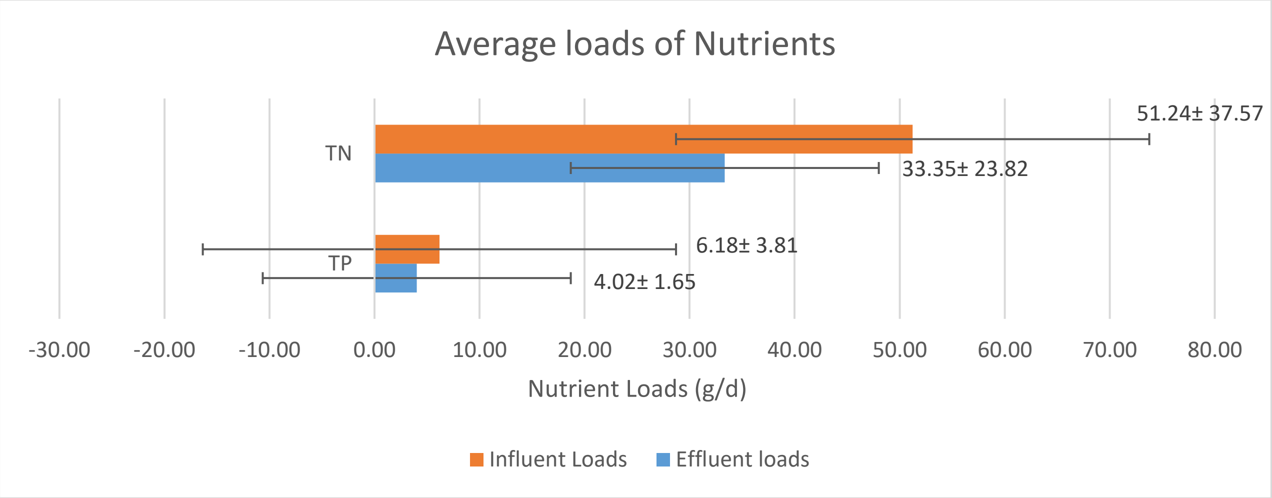

Figure 4-4: Average loads of Nutrients in the ABR influent and effluent

[Average values ± Standard deviations, n=8]

The anaerobic baffled reactor was able to achieve removal efficiencies of 34.93± 2.94 % and 34.91± 31.45 % for TP and TN respectively.

Sorption of the particulate and soluble phosphorus took place in the anaerobic filter found in the last compartment of the ABR which is made up of gravel. However, since gravel has limited sorptive capacity (Tatoulis *et al*., 2017), the removal of TP was generally poor. The ABR effluent averaged a concentration of 8.11±3.13mg/l with a range of 3.786-11.756 mg/l as seen in Table 4-2. This was similar to that reported by Hudson (2010) for an ABR study in South Africa. Hudson (2010) reported effluent values ranging between 10.3 mgP/l and 26.2 mgP/l.

In the ABR, organic nitrogen is broken down by way of the nitrogen cycle and is thus removed as nitrogen gas through the pH-sensitive sequential change processes of ammonification (organic nitrogen to ammonia), nitrification (ammonia to nitrites by nitrosomas & nitrites to nitrates by Nitrobacter) and denitrification (nitrates to nitrogen gas by denitrifying bacteria). The growth and action of these bacteria is favoured by optimal pH ranges (5.7 – 8) which were achieved by the ABR in this study (5.91-7.38). However, some parts of the aforementioned nitrogen cycle such as nitrification are, to a great extent inhibited by the anaerobic conditions in the ABR. The low nitrification rates implied that the TN was not undergoing the full nitrogen cycle through which it would otherwise get eliminated from the system. This explains the poor removal efficiency of nitrogen from the ABR (34.91± 31.45%).

4.3.1.4 Temperature

The temperature of the greywater from the kitchen ranged from 21.436 to 25.4°C while that from the anaerobic baffled reactor ranged from 21.068-25.3°C. There was no significant difference between the temperature of the greywater from the kitchen to that after treatment from the anaerobic baffled reactor (p = 0.875). This maintenance in the general temperature could be caused by a shift in bacterial populations from one partition to another (Barber & Stuckey, 2000). These bacteria carry the temperature conditions of one compartment to the next while they shift which increases protection against temperature changes.

4.3.1.5 pH and Alkalinity

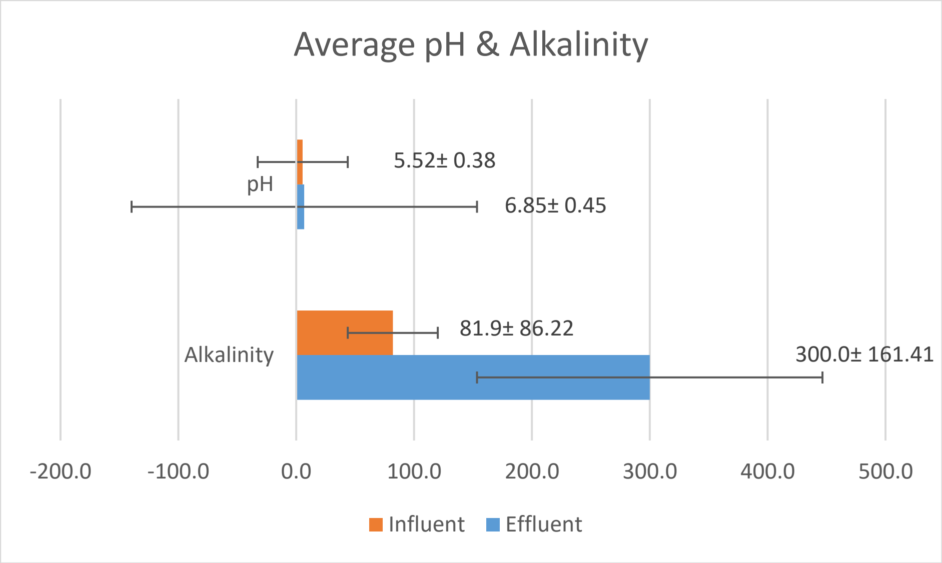

Figure 4-5: Average pH and Alkalinity of the ABR influent and effluent

[Average values ± Standard deviations, n=8]

Despite the numerical change in pH from strongly acidic (4.7932 - 6.12) as seen in Table 4-1 towards neutral (5.91-7.38) as shown in Table 4-2, there wasn't a significant difference between the pH of the ABR influent and effluent (p = 0.003). The average pH value achieved in this study (6.85± 0.45) was close in range to that reported by Busari (2018), 7.27, in a study on an ABR's greywater effluent for use in agriculture in South Africa. This pH provides a conducive environment for the degradation of the organic waste.

The acidity of the influent favoured the occurrence of the first three anaerobic processes as they can work over a broad range of pH ranging from 4 to 8.5 (Pirsaheba *et al*., 2014). The Volatile Fatty Acids (VFAs) produced during acidogenesis get consumed by methanogens during the last process of the anaerobic digestion. From this reaction, methanogens produce methane and bicarbonate alkalinity. The alkalinity they produce helps buffer the acid produced by the volatile acid formers (Ferraz, Bruni, & Del Bianchi, 2009). This increment in alkalinity (from 81.9±86.22 mg/l $CaCO_3$ to 300±161.41mg/l $CaCO_3$) can back the consequential increment in pH of the ABR effluent that is, from 5.52±0.38 in the influent to 6.85±0.45 in the effluent as shown in Figure 4-5. However, no significant statistical difference was observed for the total alkalinity for the influent and effluent of the ABR (p = 0.007). It is worth mentioning that the acid buffering done by alkalinity ensures a favourable environment for bacteria to breakdown pollutants as their action would be inadvertently driven down by an otherwise low pH (Trygar, 2014).

4.3.1.6 Fats, Oils and Grease

The fats oil and grease removal efficiency in the anaerobic baffled reactor was on average 88.59± 29.63% as shown in Figure 4-1.

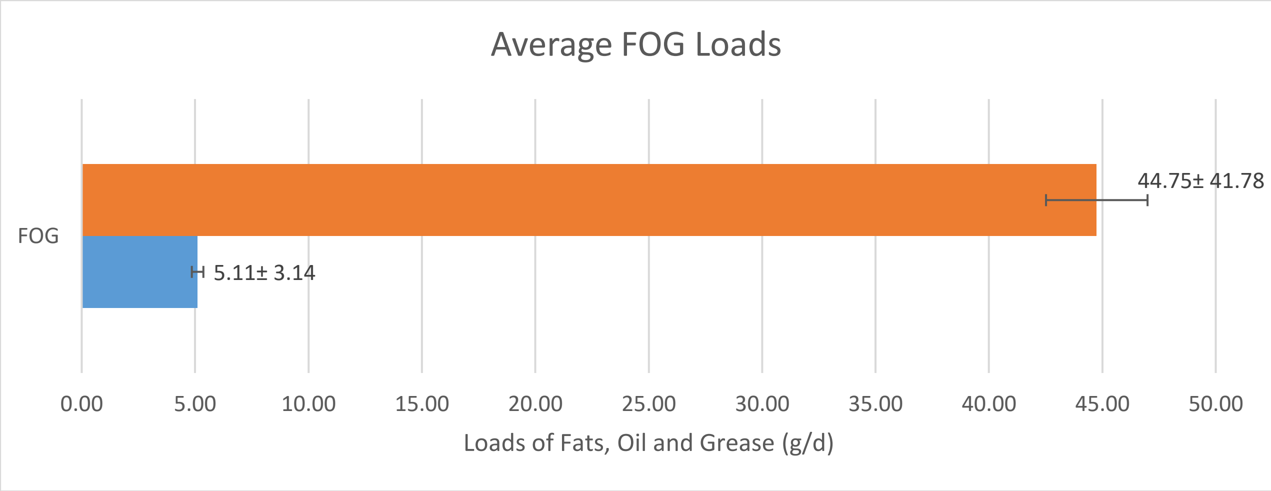

Figure 4-6: Average loads of Fats, Oils and Grease in the ABR influent and effluent

[Average values ± Standard deviations, n=8]

There was no significant difference observed between the influent and effluent load for the FOG (*p* = 0.025) however the numerical difference is because FOG is less dense than water, it floats on top of water. By so doing, the effluent that flows out of the ABR leaves behind a large amount of floating FOG substances since the effluent pipe was properly constructed to be below the water column level.

4.3.1.7 Faecal Coliforms

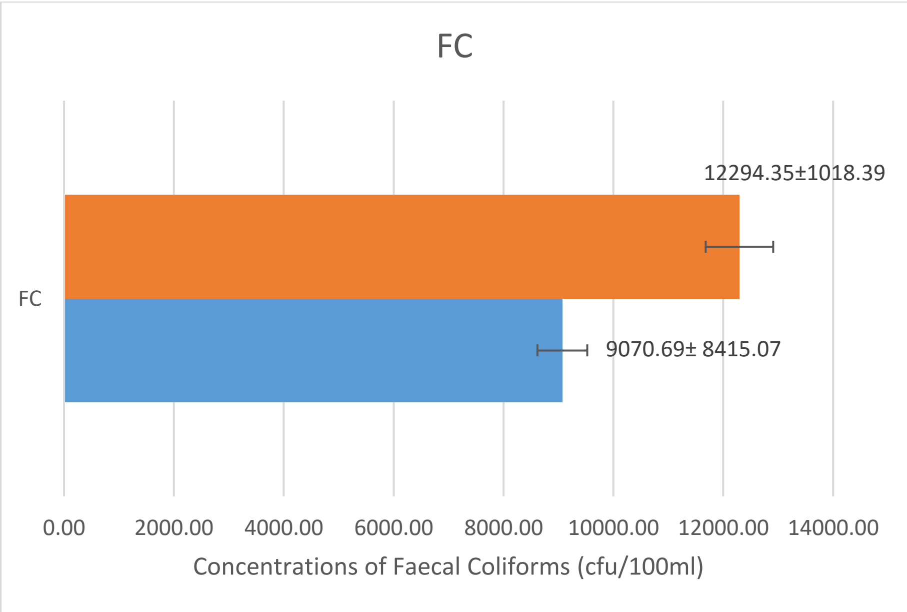

Figure 4-7: Average concentrations of Faecal coliforms in the ABR influent and effluent

[Average values ± Standard deviations, n=8]

The ABR achieved a removal efficiency of 26.22% for faecal coliforms. The difference between the influent FC concentration and effluent showed no significant statistical difference (p=0.5). The removal of pathogens in an anaerobic baffled reactor is documented by Nasr et al (2009) as deficient. The study attributes this to the anaerobic process which only partially removes these pathogenic organisms. For the anaerobic process to achieve FC removal, it requires thermophilic temperature (41-121°C) and long retention times (3 to 5 days). The anaerobic baffled reactor in consideration for greywater treatment was designed with a 36- hour retention time and this is the likely cause for the deficient removal of faecal coliforms by the ABR.

4.3.2 Treatment performance of the different media in the Constructed Wetland

Given the use of different substrate media, the treatment efficiency assessment of the CW was done comparatively for the three media.

4.3.2.1 pH and Alkalinity

Generally, across all the three media, there was a general increase in the pH values in the effluent compared to the effluent as seen in figure 4-8. This could be attributed to the use of organic acids from the wastewater by the horsetail reed in its growth mechanism (Ijaz, Iqbal, & Afzal, 2016). There was no significant difference however in the pH of the effluent from the different media (p = 0.90).

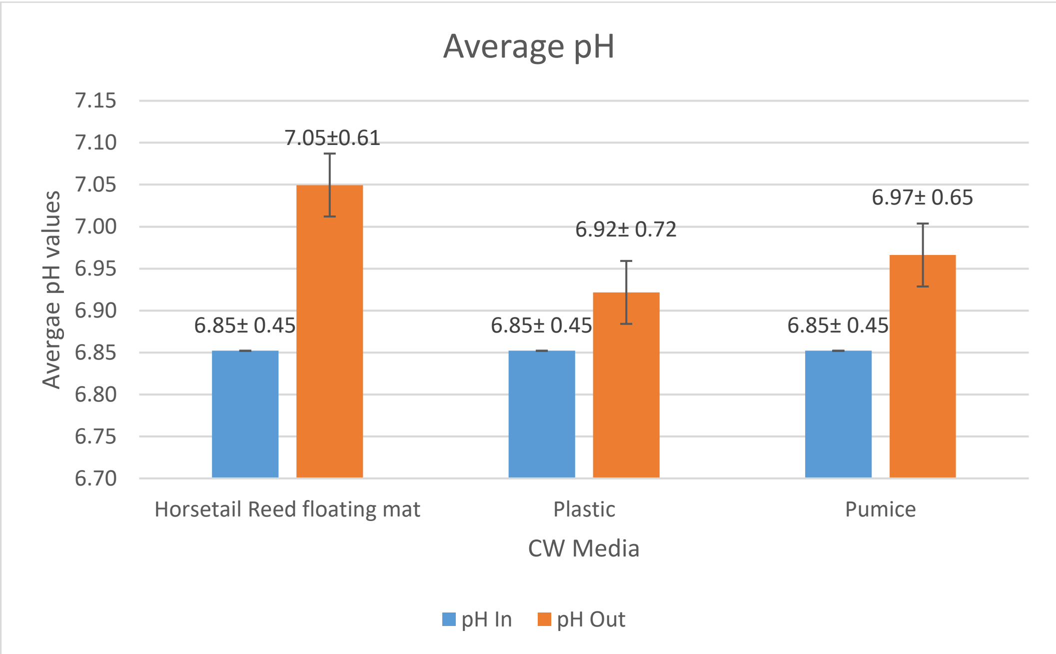

Figure 4-8: Average pH values in the CW influent and effluent

[Average values ± Standard deviations, n=8]

Average alkalinity levels in the constructed wetland effluent were observed to be 289.85±177.78mg/l for the horsetail reed floating mat, 305.02±205.77mg/l for the plastic and 283.66±184.38mg/l for pumice as seen in table 4-2. There was no significant statistical difference in the alkalinity values for the effluent from the various media (p = 0.3). There was a general decrease in the alkalinity of the effluent compared to the influent across the different media as seen in figure 4-9 which likely, confirms the low total nitrogen removal efficiencies since nitrification consumes alkalinity (Kadlec & Wallace, 2009).

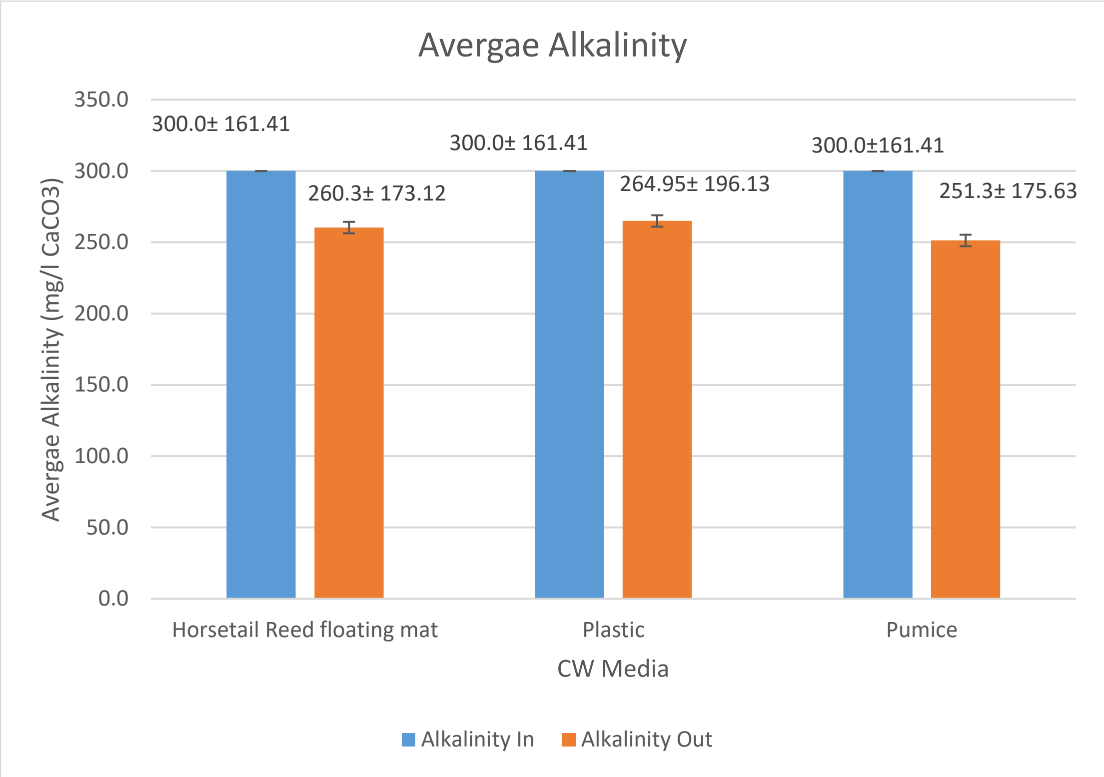

Figure 4-9: Average alkalinity in the CW influent and effluent

[Average values ± Standard deviations, n=8]

Biological processes like nitrification and anaerobic digestion rely on alkalinity (Trygar, 2014). Certain classes of aerobic bacteria, called nitrifiers use ammonia (NH_3) for food instead of carbon-based organic compounds. This implies that the nitrification process consumes ammonia which happens to be a major contributor to the alkalinity of the water. In fact, during nitrification, 7.14 mg of alkalinity as $CaCO_3$ is destroyed for every mg of ammonium ions oxidized (Trygar, 2014).

Therefore, ideally, the greater the difference between the average influent and effluent alkalinity values, the greater the corresponding nitrification rate. With this, the ranking of the CW media in terms of difference between average influent and effluent for alkalinity values should be the same as that for removal of TN. This line of thought holds for Pumice but not for the CW with plastic media and the horse tail reed floating mat.

Basing on the ranking for TN removal efficiency, plastic comes second after pumice and the horse tail reed floating mat third yet given the alkalinity values the horse tail reed should come second then plastic third. This may be attributed to the higher rate of denitrification than nitrification. Denitrification tends to add alkalinity to the water. The alkalinity gain per mg of nitrogen is only one-half of the loss caused by nitrification (Lemmons, 2017). The higher denitrification rate than nitrification explains the higher alkalinity value for plastic than the floating mat.

4.3.2.2 Solids

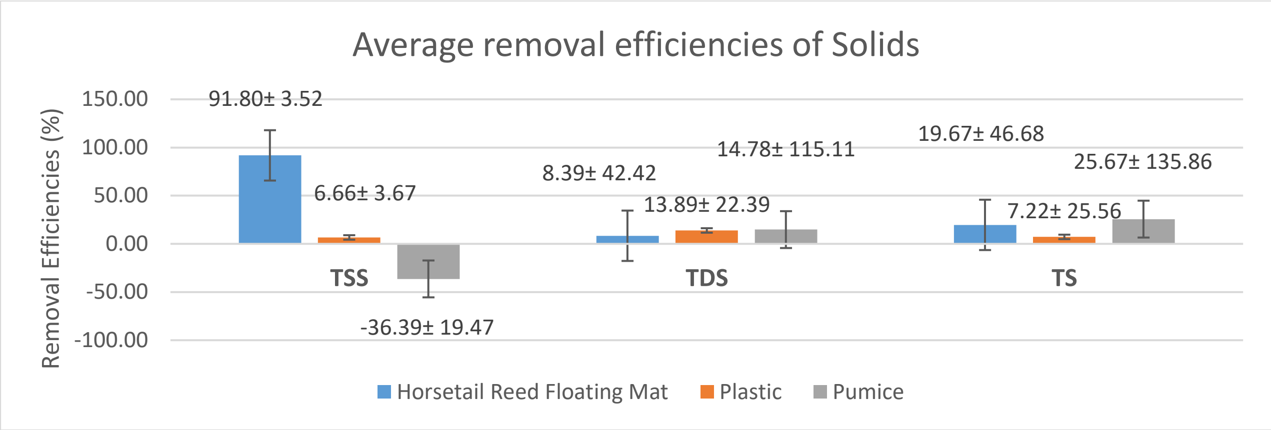

Figure 4-10: Average removal efficiencies of Solids in the CW

[Average values ± Standard deviations, n=8]

From figure 4-10, the horse tail reed floating mat achieved the highest removal of suspended solids with 91.80±3.52% efficiency followed by plastic (6.66±3.67%) and pumice (-36.39±19.47%). The statistical difference for the removal efficiency values of TSS for the different media was found to be significant ($p = 0.0165$). The litter trap and hanging root-biofilm network of the horse tail floating mat likely intercepts the fine suspended solids which adhere to the biofilm surface there (Kadlec & Wallace, 2009). The root biofilm network is also responsible for lowering the velocities of the incoming wastewater which allows for sedimentation of the particulate and relatively heavier solids. Furthermore, the horse tail reed floating mat enhances sedimentation by reducing wind-induced turbulence and mixing (Headley & Tanner, 2012). These processes therefore contributed to the relatively higher removal efficiency of suspended solids by the horse tail reed floating mat. The findings in this study with regard to removal of suspended solids by the horse tail reed floating mat are in line with those reported by Wahyudianto et al., (2019). The latter in their study, using a floating mat planted with *equisetum hyemale (horse tail reed)* for wastewater treatment reported a removal efficiency of suspended solids from 34 to 93%.

The low removal efficiency of TSS by the plastic (PET bottle tops) may be attributed to the difficulty of the much-needed biomass attaching onto the smooth PET material (Lapo et al., 2018) and the longer time it would take for the biofilm to build inside the PET bottle cover (Zidana et al., 2015) since the biomass is needed to trap suspended solids.

The macro-pore nature of the pumice used could be a plausible characteristic that caused the results to reflect a higher suspended solids concentration in its effluent. Kuslu & Sahin (2013) carried out a study in which they observed increase in suspended solids in the effluent from pumice media following an increase in flow pressure conditions resulting in the release of previously entrapped suspended solids. When they used pumice with a smaller surface area (less susceptible to pressure changes), they achieved an average TSS removal of 79.18%.

4.3.2.3 BOD_5 & COD

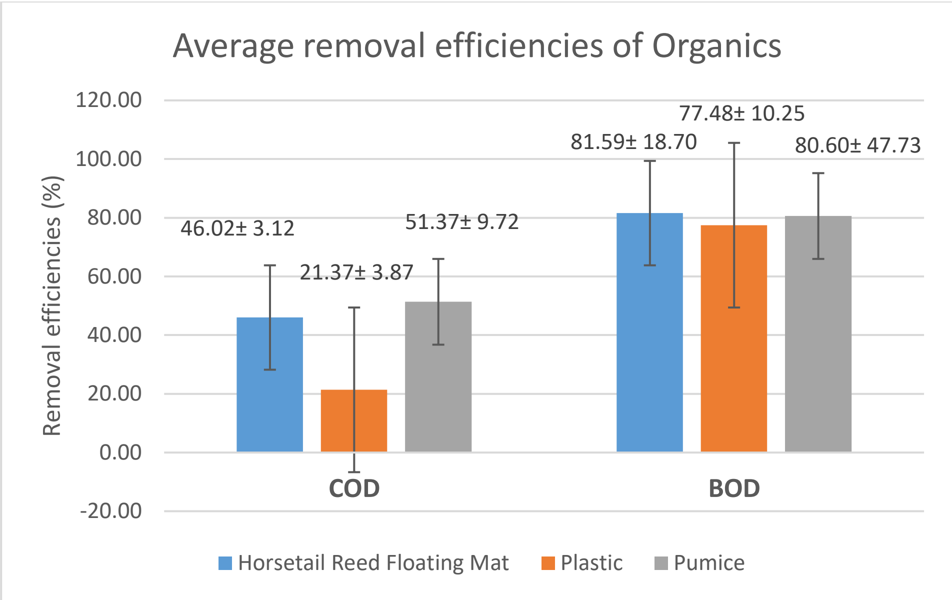

Figure 4-11: Average removal efficiencies of Organics in the CW

[Average values ± Standard deviations, n=8]

Figure 4-11 shows what the average removal efficiencies of BOD and COD across the different media of the constructed wetland. The difference between the organic matter removal efficiencies across the media was found not to be statistically significant COD ($p = 0.79$) and BOD_5 ($p = 0.92$) despite a relatively higher value recorded for the horse tail reed floating. Generally, COD and BOD_5 are removed when particulate organic matter is trapped, absorbed or consumed by the microbial growth and also transformation of some inorganic matter. For these processes to happen, the substrate must have a conducive surface area that can enable growth and reproduction of micro-organisms (Lu et al., 2016).

The horse tail reed floating mat achieved on average 46.02±3.12% removal efficiency of COD and 81.59±18.70% of BOD_5 as seen in Figure 4-11. This may be due to the entrapment of particulate organic and inorganic matter in the hanging root structure of the horse tail reed above the water column. The root zone also provides attachment sites for microbial films increasing biological activity per unit area (Dotro et al., 2017). These biofilms degrade the organic matter within the water. In addition, the hanging root network favours the rather slow process of sedimentation by reducing the velocity of incoming wastewater and intercepting the sediment (Kadlec & Wallace, 2009) which then removes particulate organic and inorganic matter.

Plastic on the other hand had the lowest removal efficiencies for both COD (21.37± 3.87%) and BOD (77.48± 10.25%) as shown in Figure 4-11. This may have been due to the absence of the much-needed biomass attaching onto the PET material (Lapo et al., 2018) and the longer time it would require for the biofilm to build inside the PET bottle cover than the outside bits (Zidana et al., 2015).

Almost like the root zone of the floating mat, pumice provides a high specific surface area which avails an enhanced zone for microbial attachment (Njau, Minja, & Katima, 2003). The biofilms degrade the organic matter within the water. It is likely that the amount of inorganic matter (non-biodegradable content) in the greywater was rather limited given the COD/BOD_5 ratio of the greywater which was largely less than 2. The latter suggests that the COD which was largely biodegradable and BOD_5, was likely removed by adsorption onto the pumice rock. According to

Çifçi & Meriç (2015), the skeleton structure of the pumice allows for movement of water and ions through open channels into and out of the crystal structure. This avails more room for adsorption of particulate matter within the water. That this is the case, explains the relatively good removal efficiency of the pumice via both COD (51.37± 9.72%) and BOD_5 (80.60± 47.73%) as seen in Figure 4-1.

4.3.2.4 Nutrients

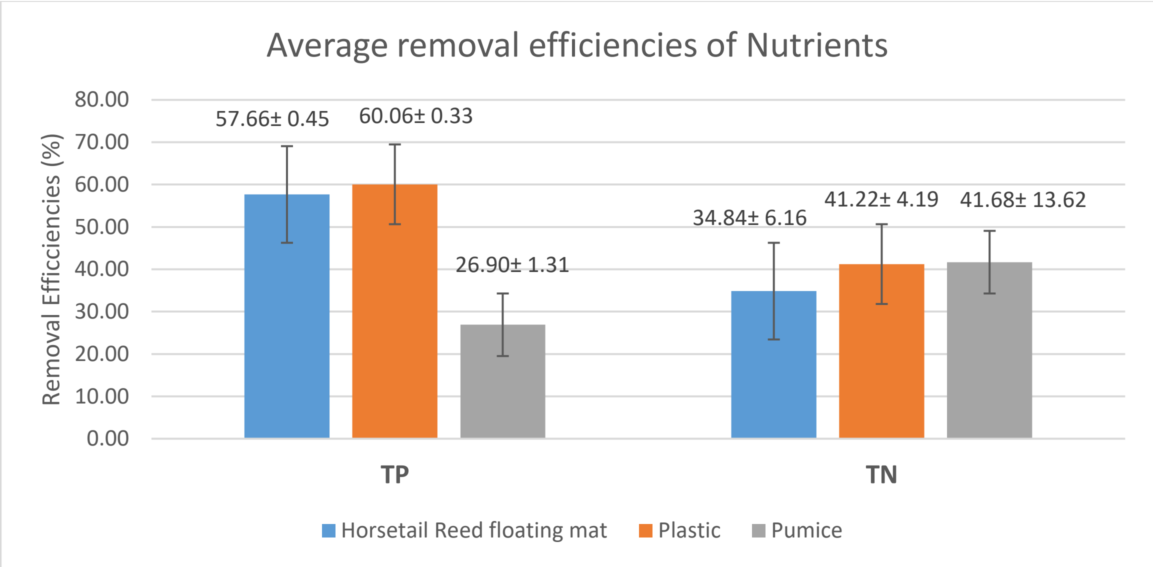

Figure 4-12: Average removal efficiencies of Nutrients in the CW

[Average values ± Standard deviations, n=8]

Figure 4-12 shows the average removal efficiencies for both phosphorous and nitrogen. The plastic achieved the highest removal of total phosphorous with (60.06±0.33%), followed by horsetail reed floating mat (57.66±0.45%) and pumice (26.90±1.31%). Statistically, there was no significant difference between the three removal efficiencies of the CW units (p = 0.949). Zhang *et al*., (2015) argue that it is possible that plant assimilation of nutrients may be almost as high in a floating treatment wetland (FTW) system compared to a sediment-rooted wetland since in a floating treatment wetland the plant roots are not in contact with the benthic sediments or soil and can only access nutrients contained within the floating mat and in the water column. This is in contrast to a sediment-bound wetland where the plant roots acquire nutrition from the underlying soil. We attributed the relatively good performance of the horse tail reed floating mat to this. Plastic, in a study by Tatoulis *et al*. (2017) was considered to have a limited adsorption capacity and most phosphorous removal was by precipitation to which its relatively better performance in this study can be attributed.

In figure 4-12 it can be observed that pumice media achieved the highest removal efficiency of nitrogen 41.68±13.62% followed by plastic 41.22±4.19% and floating mat 34.84±6.16%. No significant statistical difference was observed among the removal efficiencies across the different media (p = 0.31) despite the relatively higher value observed for the pumice. The higher removal efficiency for pumice can be attributed to rigid nature of the pumice rock which allows biofilms to firmly attach to it. The void spaces present in the plastic media provide a favorable growth area for biofilms in which the organisms responsible for TN removal might be found (Tatoulis et al., 2017).

The biofilms capture matter which might contain particulate nitrates. However, as mentioned earlier the capacity of plastic to hold onto these biofilms is rather low which implies that nitrate containing biofilms get detached back into the water which reflects a rather low TN removal efficiency of the medium (Morton & Auvermann, 2001) .

The low removal efficiency of nitrogen by the horse tail reed floating mat can be attributed to the fact that the floating mats physically shade the water column which reduces photosynthetic organism activity and production of dissolved oxygen (Borne, Fassman-Beck, Winston, Hunt, & Tanner, 2015). This creates anoxic conditions beneath the mat. These conditions, although they increase the extent of favorable conditions for denitrification, inhibit the rate of nitrification which must occur prior to denitrification. This generally inhibits the entire process of TN removal in the floating mat.

4.3.2.5 Fats, Oils and Grease

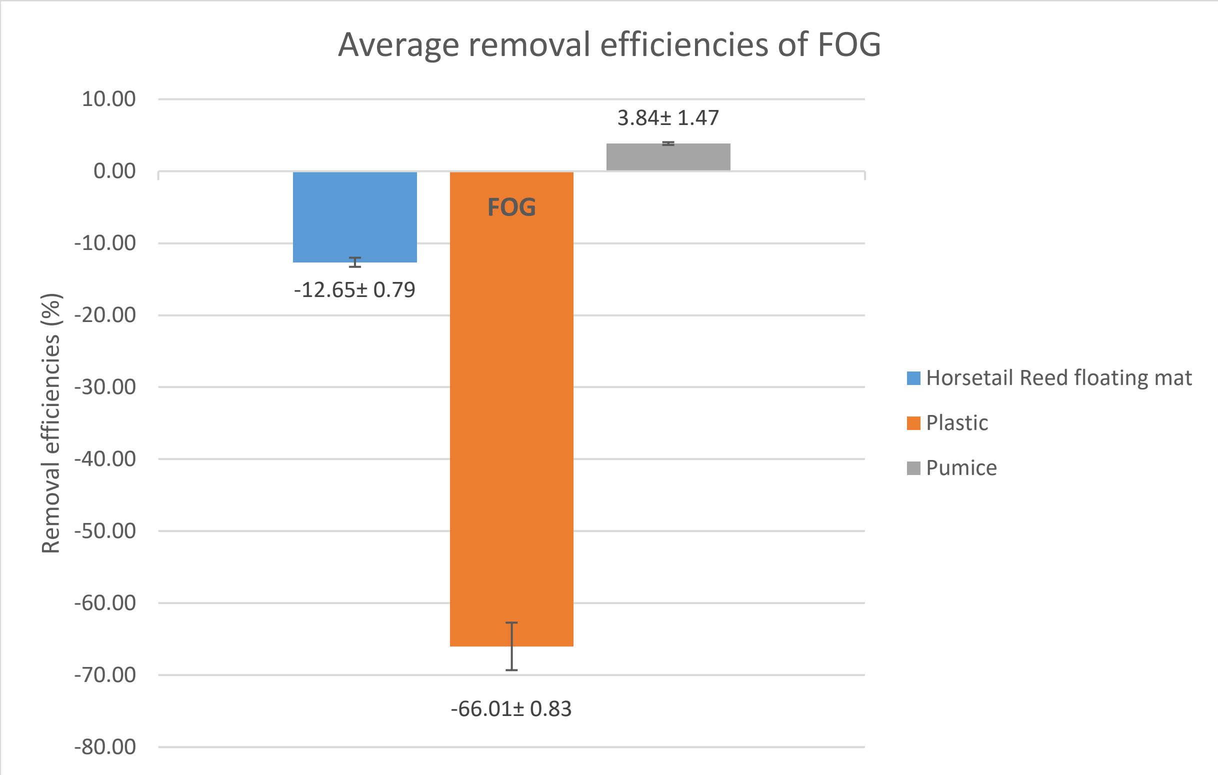

Figure 4-13: Average removal efficiencies of Fats, Oils and Grease in the CW

[Average values ± Standard deviations, n=8]

From Figure 4-13, the FOG removal efficiencies of all the CW media (plastic, pumice and horse tail reed floating mat) were generally low. The removal efficiencies across the three units (plastic, pumice and horse tail reed floating mat) exhibited a significant difference (p = 0.0019). The low removal efficiencies could be due to the occurrence of humic substances which produce oily matter in the effluent. Despite the CW with pumice having a positive removal, it extremely low (3.84± 1.47%) which speaks to the removal efficiency being poor as well. Their occurrence can be evidenced from the yellowish/brownish colour observed in the CW effluent. Humic acids originate from the biological degradation of organic matter, being the unbiodegradable fraction of organic matter (Hoffmann et al., 2011).

In addition, the anoxic conditions found near the root zone area of the CW do not offer a conducive environment for the biodegradation of oil pollutants which works best under aerobic conditions

(Kadlec & Wallace, 2009). This justifies the low removal efficiency of the fats oil and grease across the media.

4.3.2.6 Faecal Coliforms (FC)

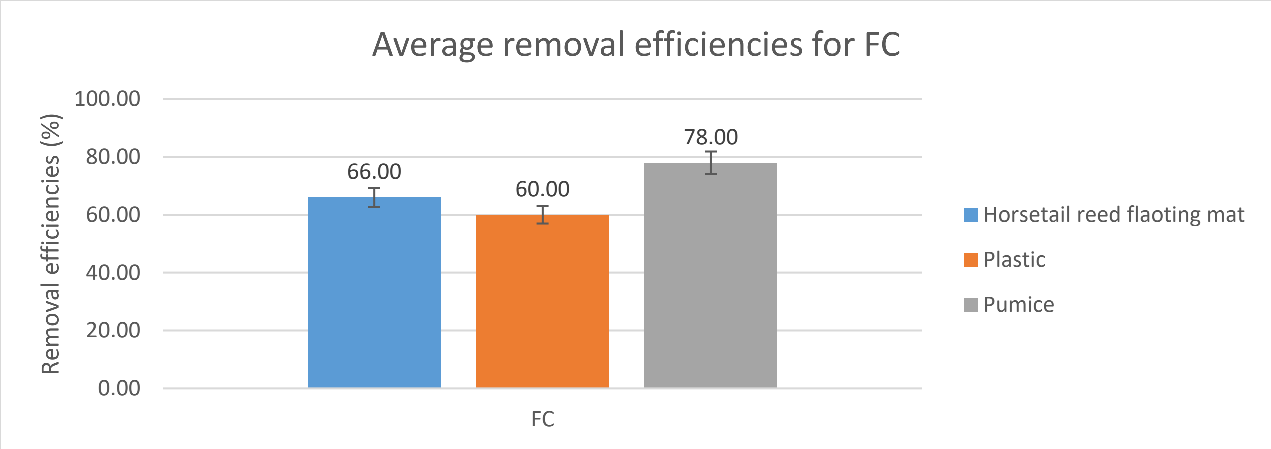

Figure 4-14: Average removal efficiencies of Faecal Coliforms in the CW

[Average values ± Standard deviations, n=8]

From figure 4-14 it can be observed that the different media achieved removal of faecal coliforms pumice (78%), plastic (60%) and horse tail reed floating mat (66%). There was no significant removal efficiency for FC b the different media ($p = 0.0063$). The generally high removal rate can be attributed to the higher retention time of constructed wetlands **Invalid source specified.**. The constructed wetland in this system was designed with a retention time of 3 days and this contributes to the pathogen removal processes of natural die off and predation as documented by Dotro, et al., (2017).

4.3.2.7 Macrophyte growth

The girth measurements of the horsetail reed macrophyte that were taken before the lockdown caused by the COVID-19 pandemic averaged at 0.97±0.22 inches with a range of 0.625 to 1.375 inches. Post-lockdown, the girths averaged at 1.80±0.19 inches with a range of 1.5 to 2.125 inches.

This 84% increment in girth may be attributed to the uptake of the nutrients from the water already within the CW compartments. The difference in sizes can be observed from Figure 4-15 and Figure 4-16 below. It can be argued that during lockdown, despite there not being any incoming greywater, the macrophyte took up nutrients from the water that was already within the system. By so doing, the shoots of the horsetail reed were able to increase in girth. This argument can be backed by the comparably low nutrient concentrations in the CW effluent for the first three sample collections done post-lockdown.

Figure 4-15: Horsetail Reed macrophyte pre-lockdown

Figure 4-16: Horsetail Reed Macrophyte post-lockdown

4.4 Assessment of the greywater viability for disposal and reuse

The treatment system was assessed for its efficiency in pollutant removal for the different parameters in order to establish whether the treated greywater was safe for discharge into the environment and reuse.

Safe disposal onto land and water

From Table 4-2, it can be seen that the treated effluent from the constructed wetland planted with horsetail reed in plastic and pumice media was largely able to meet the criteria for safe discharge into the environment (both water and on land) for most of the parameters except TN. This implies that the water from the constructed wetland, once disposed into a water body can exacerbate the problem of eutrophication in the water. The system therefore achieves significant removal of pollutants and the effluent is safe for discharge into the environment without causing significant harm to it and no public health threat.

Table 4-3: Comparison of Average CW effluent pollutant concentrations with NEMA discharge standards

Parameter	Average Effluent Concentration			**Maximum Permissible Concentration (NEMA)***
	Horsetail Reed Floating Mat	Plastic	Pumice	
pH	7.05±0.61	6.92±0.72	6.97±0.65	**6.0-8.0**
Turbidity (NTU)	17.38±10.97	15.06±7.49	17.51±15.24	**300**
TSS (mg/l)	3.1±3.32	24.68±46.33	31.6±54.31	**100**
TN (mg/l)	37.67±37.73	28.61±43.97	16.56±22.98	**20**
BOD (mg/l)	18.79±12.89	19.89±32.3	15.69±13.26	**50**
COD (mg/l)	30.05±11.16	38.65±58.55	24.96±11.49	**100**
TP(mg/l)	3.55±2.69	3.63±3.21	4.78±2.56	**10**
Colour (TCU)	164.82±88.5	137.15±91.72	270.6±180.48	**300**
FOG (mg/l)	13.65±8.83	13.61±11.28	9.57±7.92	**10**

[Average values ± Standard deviations, n=8]

***The National Environment Standards for Discharge of Effluent into Water or on Land Regulations (S.I. No 5/1999)**

The treated effluent was also assessed to determine its reuse viability. In this study, we only considered the most common uses of reclaimed greywater which are irrigation and toilet flushing. These are also the biggest consumers of water amongst the reuse options that have been identified in literature.

Agriculture (Irrigation)

Table 4-4: Comparison of Average CW effluent pollutant concentrations with Allowable concentrations for reuse in agriculture

[Average values ± Standard deviations, n=8]

Parameter	Average Effluent Concentration			**Maximum Allowable Concentration**
	Horsetail reed floating Mat	Plastic	Pumice	
pH	7.05±0.61	6.92±0.72	6.97±0.65	**6.5 – 8 [1]**
Turbidity	17.38±10.97	15.06±7.49	17.51±15.24	**≤ 2 NTU (NR)[2]**
TSS (mg/l)	3.1±3.32	24.68±46.33	31.6±54.31	**≤30 (R)[2]**
TDS (mg/l)	539.31±246.12	470.65±219.2	477.05±154.96	**450 – 2000 [1]**
FoG (mg/l)	13.65±8.83	13.61±11.28	9.57±7.92	**<10[3]**
TN (mg/l)	37.67±37.73	28.61±43.97	16.56±22.98	**5 – 30 [1]**
BOD_5 (mg/l)	18.79±12.89	19.89±32.3	15.69±13.26	**≤10 (NR)[2] ; ≤30 (R)[2]**

1 – FAO guidelines (1994) for slight to moderate restriction during handling of the treated greywater adapted from Imhof & Muhlemann (2005); ***2*** – Adapted from Boyjoo *et al*. (2013); Ghaitidak and Yadav (2013); Kimwaga (2014) and Li *et al*. (2009), proposed guidelines for non-potable reuse of greywater based on previous studies. Taking into consideration the already existing guidelines, Vuppaladadiyam, *et al* (2018), in a review paper, proposed updated guidelines which were considered in this study; R – Refers to restricted use of the treated greywater that is; limited or no human body contact, NR – Refers to non-restricted use of the treated greywater that is - an element of body contact is involved; ***3*** – Central Pollution Control Board guidelines (2012) adapted from Ghaitidak and Yadav (2013).

It can be inferred from Table 4-3 that the effluent from the different CW media (plastic and pumice) and the horsetail reed floating mat in this study, only met a few of the criteria for use in irrigation in agriculture.

All three CW units did not produce effluent that complied with the criteria for turbidity, FOG and BOD_5 for non-restricted use. Turbidity affects the social acceptability of the treated greywater. It is difficult for a person to freely use water to which a colour can be attributed. Psychologically, such water is deemed dirty.

FOG build-up in irrigation pipes can eventually cause blockages of these pipes which reduces on the scheme efficiency altogether. In addition, FOG can reduce the pore space available for water percolation and infiltration which effectively reduces on the drainage of soil.

The BOD_5 non-restricted use criteria can be applied to food crops to be consumed uncooked such as vegetables and fruits (Vuppaladadiyam, et al., 2018). In essence, the effluent from the treatment plant in this study cannot be used to irrigate a fruit farm due to the risk of contamination.

The effluent from the horsetail reed floating mat and plastic media had excess total nitrogen which, depending on the soil content and type of crops, can increase succulence beyond desirable levels, reduce sugar content in some crops like grapes and also lead to yield of weak stems in grain crops (WHO, 2006). It can also delay maturity of common fruits like avocado which leads to a poor-quality harvest and consequently low marketability of the product (Ayers & Westcot, 1994).

Plastic and Pumice effluents failed to meet the criteria for TSS. Suspended solids, just like FOG, can block the irrigation system pipes which increases maintenance costs of the scheme. Also, they can clog soils which reduces the infiltration rate thus rendering irrigation less effective.

The pH level of the CW effluent was within a range that is considered neutral and thus favours crop growth and also does not corrode the irrigation pipes as would be the case had it been acidic (Busari, 2018).

Toilet Flushing

Table 4-5: Comparison of Average CW effluent pollutant concentrations with Allowable concentrations for use in toilet flushing

[Average values ± Standard deviations, n=8]

Parameter	Average Effluent Concentration			**Maximum Allowable Concentration**
	Mat	Plastic	Pumice	
pH	7.05±0.61	6.92±0.72	6.97±0.65	**6 – 9** [2]
Turbidity	17.38±10.97	15.06±7.49	17.51±15.24	**<= 2 NTU (NR)**[2]
BOD (mg/l)	18.79±12.89	19.89±32.3	15.69±13.26	**<=10 (NR)**[2]

1 – FAO guidelines (1994) for slight to moderate restriction during handling of the treated greywater adapted from Imhof & Muhlemann (2005); ***2*** – Adapted from Boyjoo *et al*. (2013); Ghaitidak and Yadav (2013); Kimwaga (2014) and Li *et al*. (2009), proposed guidelines for non-potable reuse of greywater based on previous studies. Taking into consideration the already existing guidelines, Vuppaladadiyam, *et al* (2018), in a review paper, proposed updated guidelines which were considered in this study; R – Refers to restricted use of the treated greywater that is; limited or no human body contact, NR – Refers to non-restricted use of the treated greywater that is - an element of body contact is involved; ***3*** – Central Pollution Control Board guidelines (2012) adapted from Ghaitidak and Yadav (2013).

All the guidelines highlighted above correspond to those applied to flushing of toilets using treated greywater in China as in De Gisi *et al*., (2016). It is noteworthy that even if the greywater had m*et al*l the necessary criteria for toilet flushing, it would require a separate system altogether in order to use it for this function. This system would be for extra treatment and chlorination to suppress the odour indoors and also to prevent growth of bio-matter in the storage unit of the greywater. All this leads to a user incurring extra costs whose payback period, given the reduction in fresh water usage is usually a long time due to the maintenance costs of the additional system.

CHAPTER 5 - CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Given the study results and their discussion in Chapter 4, the following conclusions can be drawn from this study.

- The study revealed that the raw water discharged from Africa hall kitchen doesn't comply with NEMA discharge standards and is therefore not safe for disposal into the environment as seen in Table 4-1.
- The study revealed that the treatment system was able to achieve significant treatment efficiency across the various pollutant parameters. The ABR achieved removal efficiency of 96.37 ± 469.56% for TSS, 34.93 ±2.94% for TP,34.91 ±31.45% for TN, 97.29 ± 588.57% COD and 93.21 ±551.82% for BOD_5. The different media in the constructed wetland achieved removal efficiencies of 82.70 ± 18.70% BOD_5 removal for the horsetail reed floating mat, 78.25 ± 10.25% BOD5 removal for plastic and 82.86 ± 47.73% BOD5 removal for pumice. For COD removal, the horsetail reed floating mat achieved 41.21 ± 3.12%, 5.77 ± 3.87% for plastic and 49.99 ± 9.72% for pumice. For suspended solids, the horsetail reed floating mat achieved a removal efficiency of 92.34 ± 3.52%, plastic achieved -12.53 ± 3.67% while pumice achieved -45.52± 19.47%.
- Pumice achieved the highest for various parameter making it the most suitable media generally.
- The following overall removal efficiencies were achieved by the treatment trains shown in the second row of Table 5-1. They were calculated based on Equation 3-3 in section 3.4.

Table 5-1: Overall removal efficiencies of the plant

	Overall removal efficiencies (%)		
	ABR + Horsetail Reed Floating Mat	ABR + Plastic	ABR + Pumice
TSS	99.70	96.61	95.05
TP	72.45	74.01	52.44
TN	57.59	61.75	62.04
FOG	87.14	81.05	89.02
COD	98.54	97.87	98.68
BOD	98.75	98.47	98.68
FC	74.92	70.49	83.77

- The system exhibits high removal rates for most of the pollutants and the treated greywater is able to meet discharge standards for effluent into water or on land (NEMA, 1999). However, the effluent does not meet reuse criteria for most of the pollutants which inhibits its reuse in the applications of toilet flushing and irrigation.

5.2 Recommendations

- Kitchen greywater requires treatment prior to discharge and people need to be sensitised about it to prevent environmental pollution given that is not safe for disposal without treatment.
- Constructed wetlands with pumice media combined with a pre-treatment ABR can be adopted for greywater treatment.
- Appropriate post treatment for pathogen removal like disinfection should be included to meet reuse criteria.
- For further research a longer study time frame should be considered to determine the optimum time for maintenance such as harvesting of macrophytes and replace media.

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CHAPTER 7 APPENDIX

Figure 7-1: Digging of holes in which to place a bucket for flow measurement via the CW

Figure 7-2: Samples being prepared for the alkalinity test