COMPARATIVE EVALUATION OF AHMADU BELLO UNIVERSITY WASTE STABILIZATION POND AND A CONSTRUCTED WETLAND

BY

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A THESIS SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES, AHMADU BELLO UNIVERSITY, ZARIA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREEE OF DOCTOR OF PHILOSOPHY IN ENVIRONMENTAL ENGINEERING

DEPARTMENT OF WATER RESOURCES AND ENVIRONMENTAL ENGINEERING,
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DECLARATION

I declare that the work in this thesis entitled **"Comparative Evaluation of Ahmadu Bello University Waste Stabilization Pond and a Constructed Wetland"** has been carried out by me in the Department of Water Resources and Environmental Engineering under the supervision of Prof. C. A. Okuofu, Dr. D.B. Adie and Dr. S.B. Igboro. The information derived from the literature has been duly acknowledged in the text and a list of reference provided. No part of this thesis was previously presented for another degree or diploma at this or any other institution.

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Sign Date

CERTIFICATION

This thesis entitled **"Comparative Evaluation of Ahmadu Bello University Waste Stabilization Pond and a Constructed Wetland"** by Michael Obiekwe Nwude meets the regulations governing the award of the degree of Doctor of Philosophy of Ahmadu Bello University Zaria, and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

With all humility and gratitude, I dedicate this work to God for His abundance grace.

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ABSTRACT

The efficiencies of organic pollutants and heavy metal removal from the wastewater of Ahmadu Bello University, (ABU), Zaria by ABU waste stabilization pond and horizontal flow sub-surface constructed wetland were evaluated and compared at seven (7) days hydraulic retention time for a period of ten (10) weeks. A constructed wetland with dimensions 14m x 3.5m x 0.45m, lined with geomembrane of polyethylene to prevent percolation of wastewater into the groundwater and filled with gravel 10-15mm size to the depth of 0.2m at the bottom, followed by sand layer 0.3-0.5mm size to the depth of 0.20m depth and 0.05m local soil was used. Influent wastewater was provided from elevated storage tank of 3000 litres to the constructed wetland through pipe network. The effluents from the wetland and waste stabilization pond of ABU were sampled for analysis. The constructed wetland was able to remove considerable amounts of the heavy metals in the wastewater of ABU. These heavy metals otherwise would have been discharged into Kubani River at the downstream of the University dam. The efficiencies obtained during the study by the constructed wetland for Pb, Zn, Mn, Mg, Ag, Co, Cr, Cd, Fe and Cu were 86.8%, 71.83%, 97.69%, 80%, 68.81%, 90%, 86.51%, 89.34%, 68.18% and 90% respectively. On the other hand, the maximum removal efficiencies measured for the ABU waste stabilization pond for Pb, Zn, Mn, Mg, Ag, Co, Cr, Cd, Fe and Cu were 10.53%, 7.64%, 6.91%, 8.07%, 8.05%, 5.8%, 4.12%, 4.61%, 11.23% and 9.91% respectively. During the same period, the constructed wetland removed TSS, FC, BOD, COD, PO_4^-, NO_3^- and NH_4^+ by 89.2%, 94.3%, 93%, 80.5%, 67.5%, 80.5% and 32.92% respectively compared with the ABU waste stabilization pond by 78.6%, 81.1%, 78.3%, 69.8%,

38.12%, 72.6% and 17.02% respectively. The result of assessment of removal efficiencies of certain organic pollutants from ABU waste stabilization pond is in conformity with the result of the previous work done by Oke et al (2006). The DO concentration increased from 2.70 – 4.70mg/L during ten (10) weeks of study. This indicates that constructed wetlands may be eco-friendly in terms of dissolved oxygen content. The average pH and temperature of effluent from constructed wetland were 7.16 and 28.03 ^{o}C respectively and they fall within the permissible discharge limits of Food and Agricultural Organisation (FAO) and World Health Organisation (WHO) Standards. A low or zero energy input was required by the constructed wetland just like waste stabilization pond , making its operation and maintenance costs much lower compared to conventional treatment systems. The results of physicochemical and biological measurements of the treated effluent by the constructed wetland fall within the permissible discharge limits of Food and Agricultural Organisation (FAO) and World Health Organisation (WHO) effluent standards, making the treated effluent amenable for wastewater reuse in agriculture. The Microsoft Office Software EXCEL XP and SPSS programs were used to derive reliable statistical efficiency models which are closely similar in goodness of fit. The statistical analysis revealed satisfactory agreement between model predictions and measurements proving the adequacy of the models. The relationship between waste stabilization pond and constructed wetland effluents are highly and positively correlated. There was statistically significant difference at $p < 0.01$ level in removal efficiencies of heavy metals for WSP and CW $F(9, 181.348) = 21.632$, $p=0.01$. In addition to reaching statistical significant, the actual difference in mean values between WSP and CW was significant too (i.e. Mean for WSP and CW = 1.667420 and 0.745740 respectively). There was also statistically significant difference at the $p <$

0.01 level in removal efficiencies of physico-chemical pollutants for WSP and CW F (9, 181.348) = 21.632, p=0.01. The actual difference in mean values between WSP and CW was also significant (i.e. Mean for WSP and CW = 29.6500 and 20.0946 respectively). This study observed that the constructed wetland significantly removed heavy metals and physico-chemical pollutants more than waste stabilization pond.

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ABBREVIATIONS

AAS	Atomic Absorption Spectrometer
ABU	Ahmadu Bello University
APHA	American Public Health Association
BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
CWS	Constructed wetland system
DO	Dissolved oxygen
FAO	Food and Agriculture Organization
FC	Faecal coliform
FEPA	Federal Environmental Protection Agency
FWS	Free water surface
HF	Horizontal flow
OM	Operation and maintenance
SF	Subsurface flow
TSS	Total suspended solid
VF	Vertical flow
WHO	World Health Organization
WSP	Waste stabilization pond
WWTP	Wastewater treatment plant

CHAPTER ONE

INTRODUCTION

1.1 Background

In many developing countries like Nigeria, the problem of environmental management is severe because of lack of strong legislation and institutional capacity for integrated planning and management especially of wastewater. It is estimated that approximately two-thirds of the population in the developing world has no hygienic means of disposing excreta and even greater number of them lack adequate means of disposing of wastewater (Mara *et al.,* 2010). The frequent outbreaks of diseases such as diarrhea, cholera, and typhoid in developing countries have been partly attributed to these depressing factors. Also haphazard disposal of untreated wastewater from households, institutions and industries has caused severe deterioration of water bodies in many developing countries.

The World Health Organization (2006) has predicted that as freshwater becomes increasingly scarce due to population growth, urbanization and, probably, climate change, the use of wastewater, excreta and greywater in agriculture and aquaculture in developing countries would become increasingly attractive. Unfortunately, in developing countries including Nigeria, emphasis is on improving drinking water quality rather than the safe and sustainable wastewater treatment and re-use. This is because as at now, the quantity of available potable water to an individual is still far below recommended levels.

Experience has shown that the conventional centralized wastewater management systems which have proved to be effective in developed countries seem to have serious operational challenges in many developing countries including Nigeria, due to the high costs of

construction and operation, maintenance of facilities, power, and lack of experienced and skilled manpower.

In recognition of this, coupled with the desire to have an efficient and cost-effective wastewater treatment system, the Ahmadu Bello University, Zaria employed waste stabilization ponds (WSPs) for its wastewater treatment. The effluents from the waste stabilization ponds are used by farmers living around the institution for irrigation. The wastewater generation in Ahmadu Bello University, Zaria cannot be devoid of any trace of heavy metals considering the various activities such as medical and science laboratories, electric and auto-mechanic workshops within the university and its environs. Heavy metals are known to be dangerous to life because they tend to accumulate in plants and animals tissues where they cause damage (Ghosh *et al.*, 2012; Shuaibu *et al*., 2013)

Studies have shown that wetland systems have potentials in controlling water pollution from domestic, industrial and non-point source contaminants (Vymazal, 2005; Rai *et al.*, 2013). Wetland systems use aquatic plants, soils and their associated micro-organisms to remove contaminants from wastewater (Sohair, *et al.*, 2013; Rai *et al.*, 2015). They are simple, effective, reliable and economical technology compared to several other conventional systems. Wetlands are transitional areas between land and water. The term "wetlands" encompasses a broad range of wet environments, including marshes, bogs, swamps, wet meadows, tidal wetlands, floodplains, and ribbon (riparian) wetlands along stream channels (UN-HABITAT, 2008).

There are various types of constructed wetland systems for treating wastewater based on the type of plants used, type of media used and flow dynamics. A constructed wetland (CW) is a biological wastewater treatment technology designed to duplicate processes

found in natural wetland ecosystems. Constructed wetland systems are either surface flow or subsurface flow wetlands that use processes such as biological, chemical, physical and microbial means for the treatment of wastewater. The surface flow wetlands are constructed to resemble natural wetlands while the subsurface flow wetland is a bed of porous media, such as sand or gravel, usually vegetated and which can either be vertical flow or horizontal flow by configuration.

1.2 Statement of Research Problem

Industrialization and urbanization in developing countries like Nigeria have brought about pollution of water bodies in urban cities with inherent consequences including compromised sanitation, public health, poor nutrient recovery in the ecosystems and pollution of freshwater resources. Unfortunately, the developing countries lack the required power and water supply, capital layout and experienced and skilled manpower to operate and maintain conventional wastewater treatment plants. This has been the major contributor to poor wastewater treatment and disposal in developing countries.

The presence of heavy metals in aquatic environments has been a matter of concern to the scientific community and public health organizations worldwide due to their persistence and toxicity (Ahmodu *et al.*, 2015; Tadele and Ariaya, 2014). The disposal of effluents containing heavy metals brings harmful consequences to both human health and the environment.

In view of this, the need to provide an efficient and cost-effective wastewater treatment system at least in small communities like the Ahmadu Bello University, Zaria becomes

imperative. The effluent from waste stabilization ponds is discharged into the drains which subsequently empty into Kubanni River, downstream of the raw water intake which is the main source of water supply in the University. The effluent from waste stabilization ponds is found to be rich in organic nutrients, and consequently, is used for irrigation by some peri-urban farmers from communities close to the university. This unregulated re-use of the effluent for irrigation of crops especially vegetables calls for the evaluation of any traces of heavy metals in it. It is known that heavy metals tend to accumulate in plants' and animal tissues causing chronic adverse health effects on consuming human.

The need therefore to develop a simple low-cost wastewater treatment technology that can effectively eliminate or at least drastically reduce the quantities of heavy metals in the wastewater becomes imperative.

1.3 Aim and Objective of the Study

The aim of this study is to evaluate the performance of ABU waste stabilization pond and constructed wetland in removing physico-chemical contaminants and heavy metals from the ABU wastewater effluents.

The specific objectives of the study are to:

1. Compare the removal efficiency of physico-chemical parameters such as pH, chemical oxygen demand (COD), biochemical oxygen demand (BOD), total suspended solid, phosphate, ammonia, nitrate and heavy metals in wastewater of ABU by waste stabilization pond and constructed wetland.
2. Modeling of constructed wetland treatment parameters.
3. Subjecting the treatment results of waste stabilization pond and constructed wetland to statistical assessment.

1.4 Justification of the Study

It is essential to understand the health implications of the substantial quantities physico-chemical contaminants and heavy metals in the wastewater generation in Ahmadu Bello University, bearing in mind the damage to human health and the environment of these water contaminants. Information from this study will add to knowledge in the field of constructed wetland in small communities, and alert the ABU community and its environs of the danger in eating vegetable grown with wastewater containing heavy metals.

1.5 Scope and Limitation of the Study

The study involves evaluation of physico-chemical contaminants and heavy metals removal from the wastewater generation in ABU by Waste Stabilization Pond and constructed wetland. After constructing the wetland, adequate time was allowed for the establishment of the aquatic plants. Subsequently, field measurements were done over a period of ten weeks. The physico-chemical properties of the wastewater measured include pH, Temperature (T), Total Suspended solids (TSS), Biological Oxygen Demand (BOD_5), Chemical Oxygen Demand (COD), Phosphate (PO_4^-) Ammonia (NH_4^+), Nitrate (NO_3^-), and Total Coliforms. The heavy metals measured include Lead (Pb), Iron (Fe), Zinc (Zn), Cadmium (Cd), Magnesium (Mg), Chromium (Cr), Manganese (Mn), silver (Ag), Copper (Cu), and Cobalt (Co).

All the construction materials, including plants, for the constructed wetland system were sourced locally. The study used standard titrimetric and instrument methods for all measurements. The major challenge of the construction of the wetland was the coarse nature of the soil particles resulting in high porosity. As a result, the excavated soil was lined with geomembrane of polyethylene to prevent percolation of wastewater into the

groundwater. It would have been desirable to run the wetland for a longer period but time could not because the PhD programme is time linked.

1.6 Description of the Project Area

Ahmadu Bello University, Zaria which is located within latitude 11^{o} 07′10″ N and latitude 11^{o} 10′27″ N, and longitude 7^{o} 37′47″ E and longitude 7^{o} 39′48″ E and at an altitude of 550-700m. Ahmadu Bello University, Zaria was established in 1962 as a regional University, until 1975, when it was taken over by the Federal Government of Nigeria. The University is the largest in Nigeria with a student population of over 35,000. It has an academic staff totaling over 2,000 in 12 faculties viz: Administration, Agriculture, Arts, Education, Engineering, Environmental Design, Law, Medicine, Pharmaceutical Sciences, Science, Social Sciences and Veterinary Medicine. The project site which is located on latitude 11^{o} 08′15″ N and longitude 7^{0} 39′25″ E, at an altitude of 685 meters lies within ABU wastewater treatment plant location (Figure 1.1).

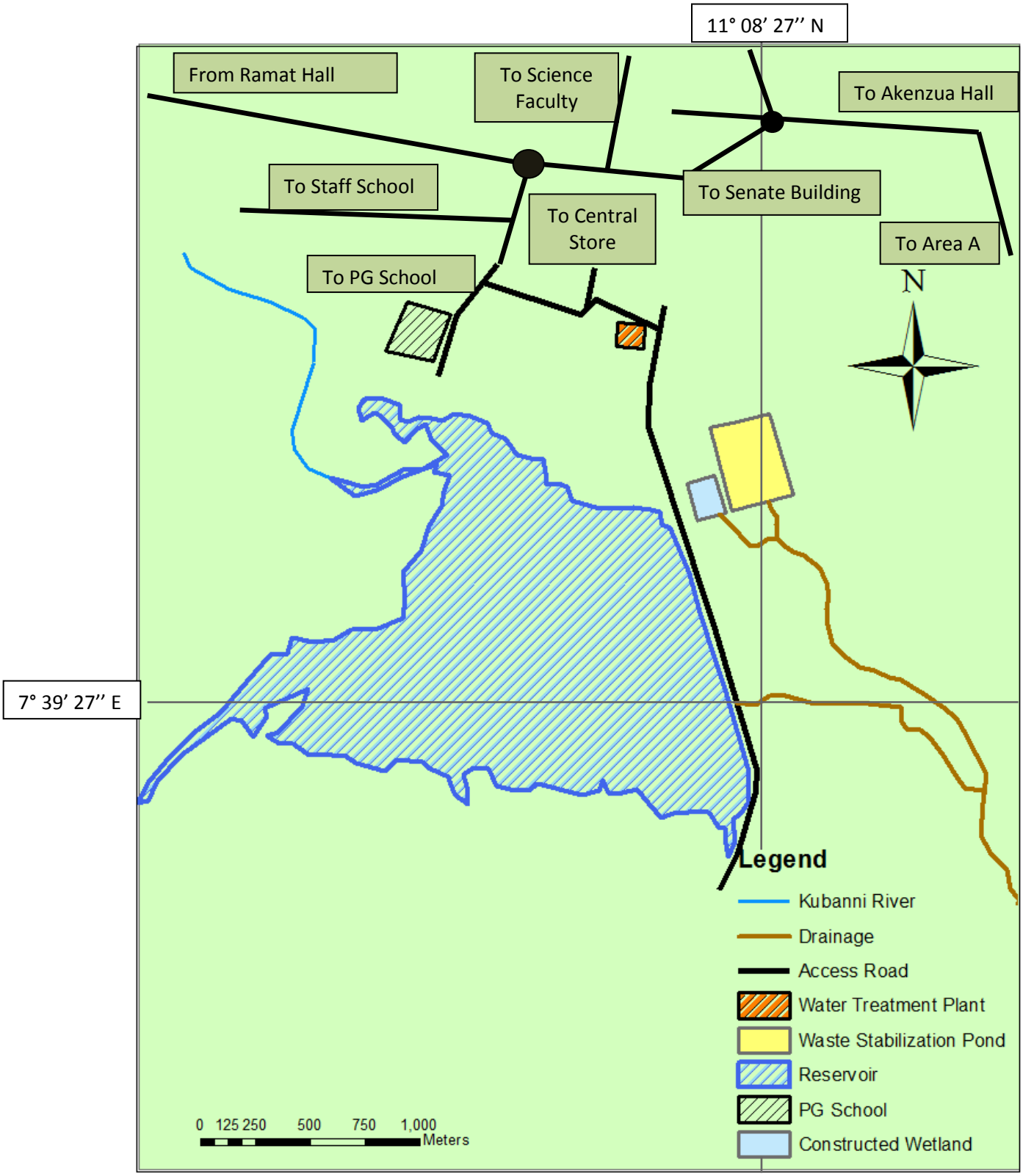


Fig.1.1: Ahmadu Bello University Wastewater Treatment Plant Location

It is about 13km from Zaria-city on the Zaria- Sokoto road, 8km to Shika and 7km from Basawa. Zaria is a very large, heterogeneous city and one of the most important cities in Northern Nigeria (Uba *et al*, 2013). Zaria itself is a very large, heterogeneous city whose 1,490,000 population comes from different parts of the world. It is second in size only to the State Capital, Kaduna. It is easily accessible from different parts of the country by air via Kaduna, Kano, and Abuja and by rail and road via Kaduna, Jos, Kano and Sokoto. Zaria is located on the great Hausa plains of Northern Nigeria, 652.6 meters above the sea level, and about 950km away from the coast.

The Zaria region is characteristically situated on part of the great Hausa plain with scattered residual rocky hills developed on granite bedrock. Zaria has a tropical continental climate with a pronounced dry season, lasting up to seven months (October - May). During the dry season, a cool period is usually experienced between November and February.' This emanates from the influence of the North-easterly (NE) winds (the Harmattan) which control the tropical continental air mass coming from the Sahara. This weather prevails over most parts of the country. The NE winds are characterized by hazy to dusty conditions and low temperatures, as low as 10^{o} C at night. In the afternoons, up to 40^{o} C is sometimes recorded. The humidity also drops to less than 15% in December/January. The rainy season lasts from May to September/October with long-term annual rainfall of c.1040mm in about 90 rain days. The relatively deep tropical ferruginous soils and climate conditions of Zaria are suitable for and sustain a good cover of savanna woodland with a variety of grasses, woody shrubs and short trees. The present vegetation may thus be described as parkland with annual grasses/shrubby cover interspersed with trees of special food and economic

values. The River Galma forms the main focus of the drainage systems in Zaria. Although the Galma carries water throughout the year, most of its tributaries dry up between January and June.

1.6.1 Brief History of the Ahmadu Bello University (ABU) Wastewater Disposal System

At the inception of the Ahmadu Bello University in 1962, a provision was made for a trickling filter to treat the sewerage from some of the students' hostels, kitchens and the academic blocks. At that time, the population of the University was barely 462. However, the use of the trickling filter was short-lived because of increased hydraulic and organic loads resulting from the increasing population. The kitchen wastes of some of the halls of residence were drained into open ditches while the rest of the buildings on the campus had separate and individual septic tanks to treat their wastewaters. The open ditches unfortunately, became a breeding ground for reptiles, rodents and mosquitoes, and produced obnoxious smells. In view of this and other reasons, a new wastewater plant was proposed for the University. In 1972, a new treatment plant called the "Oxigest package plant model- R", operating on the same principle as the activated sludge plant (ASP) was installed. The plant measured about 18m in diameter and 5m in height with a smaller cylindrical annular wall measuring about 8.5m in diameter was fitted into the larger one and divided into three compartments namely: contact, re-aeration and aerobic digester compartments. Other parts of the plant include a walkway across the top of the plant, two air blowers and a settling basin (Mustafa, 1973). Unfortunately, the mechanical sewage

treatment oxigest plant model- R could not yield the desired result due to overloading and lack of spare parts for maintenance; resulting in the mal-function of the plant.

A proposal to replace the activated sludge plant (ASP) with a more effective and sustainable system that can carry a higher loading was made, hence in 1979 a waste stabilization ponds (WSP) system was designed and constructed as the first of its kind to be implemented in Nigeria (Lukman, 2009; Lukman *et al*., 2009a; Otun *et al.*, 2009). The WSP is located at the south-eastern corner of the main campus. It is adjacent to the downstream side of Kubanni dam and ABU water treatment works. The sewage from the university is channeled through a well laid sewerage to the WSP treatment plant. The influent from the entire sewer networks enters the WSP through a screening tank where larger floating materials are trapped and removed and then passed through a measuring flume channel to a dividing chamber from where the flow is re-distributed into two parallel facultative pond systems. The effluent from the system of ponds discharges through a common outlet to a gully leading into River Kubanni. The system operates such that both sets of the ponds can operate simultaneously. The pond system has an interconnection of pipes designed that the influent to one set of the ponds can be diverted to another if any fault occurs. The WSP has been in operation for the past three decades and has been well maintained. During the dry season, the effluent is used by the villagers for irrigation (Okoliko, 2005).

Agunwamba *et al*. (2003), Hamzeh and Ponce, (2007) and Mara (2004) described WSPs as large shallow basins enclosed by natural embankments in which decomposition of organic matter in wastewater is processed naturally (biologically). Oke, *et al*. (2009) reported that biological treatments of domestic and industrial wastewaters have increased tremendously,

because they have been found to be appropriate for most developing nations, where land and labour are still relatively cheap and the climate favours natural degradation of organic wastes. Consequently, biological treatment of these wastewaters requires a combined process of carbon and nitrogen removal (Oke, *et al*, 2006, 2009). According to Agunwamba (1994), the high occurrence of sunlight in Nigeria and lack of adequate facilities for maintenance of complex mechanical systems, make WSP very suitable for the Nigerian environment.

The ABU WSP has six numbers of ponds comprising two facultative ponds and four maturation ponds arranged in series as shown in figure 1.2.

According to Otun *et al.*, (2009), the designed dimensions of ABU WSP are 181.3m x 70m x 1.5m, 64.8m x 33.7m x 1m and 53.5m x 36.6m x 1m for facultative, first and second maturation ponds respectively. Oke *et., al* (2006) assessed the performance of ABU waste stabilization pond and the result indicates that the average removal efficiencies of BOD, COD, SS, NO_3^- and FC are 93.58%, 96.4%., 66.1%, 50.04% and 99.3% respectively. The advantages of stabilization ponds over other processes include inexpensive design and construction, lower power requirements, high resistance against organic and hydraulic shock loads, high efficiency in pathogen removal and the possibility of using algae as a high quality protein food source (Mara, 1976; NSFC, 1997). However, the disadvantages generally claimed for these ponds are higher land requirements, variable operation from season to season, odours, reproducing flies and other insects, presence of algae in the effluents, the need for algae removal, and high costs of collection system to convey municipal wastewater to the treatment site in the suburbs (Lukman *et al.*, 2009b; NSFC, 1997). According to Adewumi *et al.*, (2005), waste stabilization ponds have been installed

in some institutions (Ahmadu Bello University, Zaria; University of Ibadan, Ibadan; IITA, Ibadan and Obafemi Awolowo University, Ile-Ife, and with increasing population in most of these institutions and sudden change in climate and wastewater quality, there is need for monitoring efficacy of biological treatment processes which depend mainly on nature.

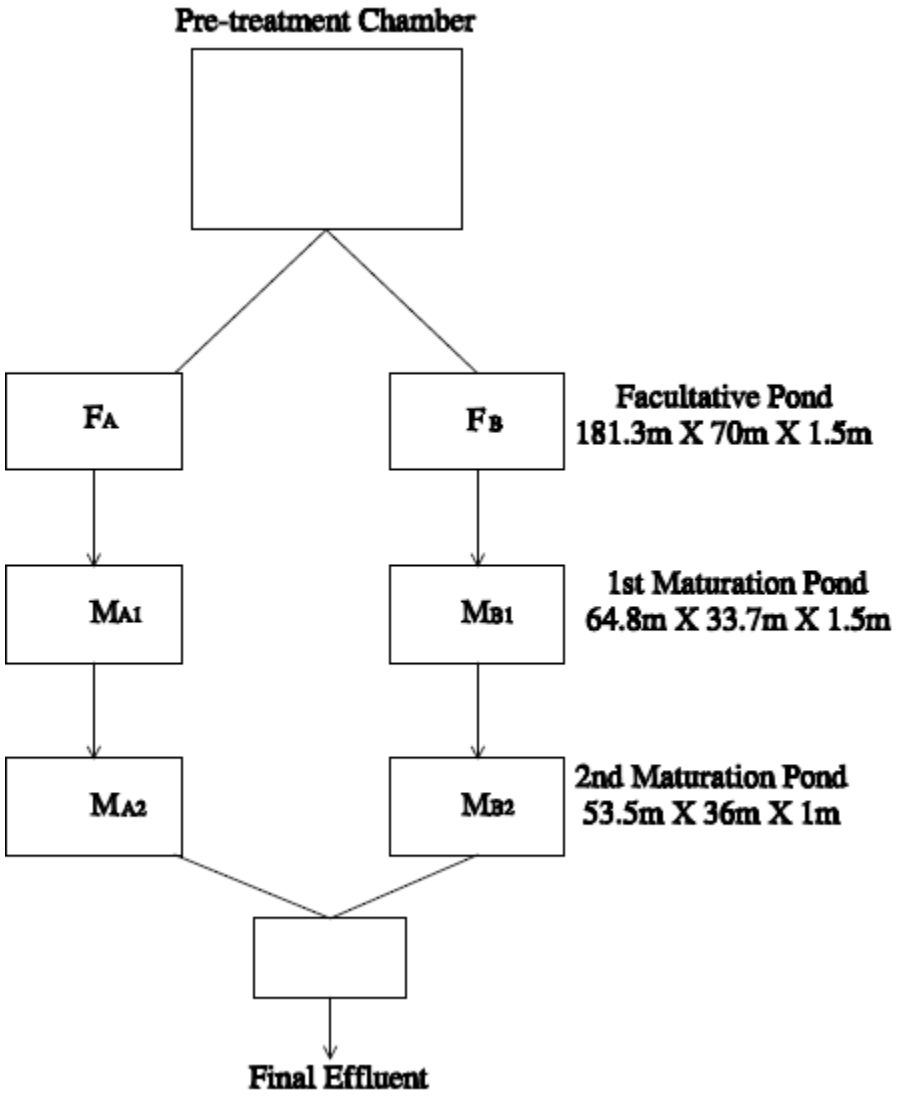


Fig.1.2: ABU Waste Stabilization pond Plan

CHAPTER TWO

LITERATURE REVIEW

2.1 Wastewater

According to Tilley *et al.* (2014) wastewater is defined as any water that has been adversely affected in quality by anthropogenic influence. Municipal wastewater is usually conveyed in a combined sewer or sanitary sewer, and treated at a wastewater treatment plant. Effluent from wastewater treatment plants is discharged into receiving water via an effluent sewer. Wastewaters generated in areas without access to centralized sewer systems rely on on-site wastewater treatment systems.

2.1.1 Wastewater constituents

The constituents in untreated wastewater can be divided into three types: physical, chemical and biological. Physical constituents include the particles or solids in the effluent which are defined as untreated, partially treated or completely treated liquid waste. Chemical constituents include nutrients and heavy metals while biological constituents include bacteria, algae and other microorganisms such as protozoa, helminthes and viruses (Crites and Technobanoglous, 1998).

2.1.2 Heavy metals

Heavy metals refer to any metallic chemical element that has a relatively high density and is toxic or poisonous at low concentrations. They are dangerous to life being and tend to accumulate in plants and animals causing chronic adverse effects on human health. They

are dangerous because they bio-accumulate, meaning an increase in the concentration in the human body over time, due to their poor metabolism. Heavy metals are environmentally stable and non biodegradable. They are introduced into human bodies through food, drinking water and air. Sewage contains heavy metals such as cadmium, zinc, nickel, lead, chromium, cobalt and copper, which are released into the river water and sediments. Their persistence in the aquatic environment leads to bioaccumulation and biomagnification into the food chain affecting the aquatic flora and fauna (Williams, 2002; Vangronsveld *et al.*, 2009; Dipu, 2013; Laurence, 2014).

Low concentrations of some heavy metals (copper, selenium, zinc) are essential to maintaining metabolism in humans, but at higher concentrations especially above recommended values, they all can lead to poisoning. Also, studies indicate that cobalt, copper, iron, manganese and zinc are needed at low levels as catalysts for enzyme catalysed activities. While, excess exposure can result in toxicity (Adeboju-Bello *et al.*, 2009). They also reported that heavy metals can cause human ill health with many symptoms depending on the nature and quality of the metal ingested. Bakare-Odumola (2005), had identified that the most common heavy metals that humans are exposed to include aluminum, arsenic, cadmium, lead and mercury. Aluminum has been associated with alzheimer and parkinson diseases, sterility and dementia (Carrondo *et al.*, 1978; Rajappa *et al.*, 2010). Kupper *et al.*, (2000) reported that arsenic exposure causes cancer, abdominal pain and skin lesions while cadmium exposure results in kidney damage and hypertension. They also reported that lead is a cumulative poison and a possible human carcinogen. According to Ahmodu *et al.*, (2015) mercury, toxicity can result to fatigue, depression, sluggishness (letheragy), irritability, and headaches. They further noted that lead and mercury can cause development

of auto-immunity in which a person's immune system attacks its own cells. This, they reported further leads to joint disease and ailment of the kidneys and nervous system.

2.2 Wastewater Treatment

Wastewater is widely treated in industrial-scale energy intensive wastewater treatment plants (WWTPs) which include physical, chemical and biological treatment processes (U.S. EPA, 2013). Treatment systems based on natural degradation processes, such as stabilization ponds and constructed wetlands, are particularly suited for domestic wastewater treatment where sufficient land is available, because they require little or no energy, and are relatively simple to operate, and show reliable treatment performance (Langergraber *et al.*, 2009; Vymazal and Kröpfelová, 2009).

2.3 Wetlands

Wetlands are defined as land where the water level is near the ground surface long enough each year to maintain saturated soil conditions, along with the related vegetation (USEPA, 2000). Natural wetlands (swamps, bogs, marshes, fens, sloughs) are being recognized for providing many benefits, including: food and habitat for wildlife; water quality improvement; flood protection; shoreline erosion control; and opportunities for recreation and aesthetic appreciation. (USEPA, 1993)

A constructed wetland is a wetland specifically constructed for the purpose of pollution control and waste management, at a location other than existing natural wetlands (Zhang *et al.,* (2010). According to Vymazal (2011), a constructed wetland can be defined as

engineered systems that have been designed and constructed to utilize the natural processes involving wetland vegetation, soils, and the associated microbial assemblages to assist in treating wastewaters. They are designed to take advantage of many of the same processes that occur in natural wetlands, but do so within a more controlled environment (Wojciechowska *et al.,* 2010)

Constructed wetlands are an engineered eco-technological system, designed with ecological principle to exploit the natural processes involving wetland vegetation, soils and associated microbial assemblages for treating wastewaters for the removal of nitrogen, phosphorus, total solids, and trace elements (Soda *et al.,* 2012; Madera-Parra *et al.,* 2013; Rai *et al.,* 2013; Nivala *et al.,* 2013; Guittonny-Philippe *et al.,* 2014). Constructed wetlands, in contrast to natural wetlands, are man-made systems or engineered wetlands that are designed, built and operated to emulate functions of natural wetlands for human desires and needs created from a non-wetland ecosystem or a former terrestrial environment, mainly for the purpose of contaminant or pollutant removal from wastewater (Baskar *et al,* 2014)

According to Kadlec and Wallace (2008), constructed wetlands can be considered as treatment systems that use natural processes to stabilize, sequester, accumulate, degrade, metabolize, and/or mineralize contaminants. Although constructed wetland applications were limited to treating primarily storm water and municipal wastewater, they are now being used in new applications and on new contaminants.

Constructed wetlands are proving to be a valid treatment option for acid mine drainage, hazardous waste site wastewaters, petroleum refinery wastes, compost and landfill leachates, agricultural wastes and pretreated industrial wastewaters, such as those from pulp and paper mills and textile mills (ITRC, 2003).

Constructed wetlands are effective and eco-friendly ways to remove suspended solids, organics, and heavy metals to improve water quality, at the same time, nutrients are recycled to be reused. Besides, constructed wetlands also provide a particular value of flooding control, studying cases for investigation and research, habitat for fish and birds as well as enhance the landscape aesthetically (Kadlec *et al*, 2000; Haberl *et al*, 2003; Vymazal, 2007; Carty *et al.*, 2008).

According to USEPA (2000) constructed wetlands are artificial wastewater treatment systems consisting of shallow ponds or channels which have been planted with aquatic plants and which rely upon natural microbial, biological, physical and chemical processes to treat wastewater. They have impervious clay or synthetic liners and engineered structures to control the flow direction, liquid detention time and water level. Depending on the type of system, they contain an inert porous media such as rock, gravel or sand.

According to Davies (2010), "depending on their design, constructed wetlands can also serve to attenuate larger storm events and reduce peak flows, offsetting the changes to flow frequency relationships caused by increased catchment imperviousness, and protecting downstream environments from erosion and flooding". He further stated that constructed wetlands also increase flora and fauna habitat in already urbanised catchments where many natural wetlands have been cleared, drained or filled. Constructed wetlands also provide passive recreation, educational and scientific studies opportunities".

2.4 History of Wetlands for Wastewater Treatment

The natural wetlands have probably been used for wastewater disposal for as long as wastewater has been collected, with documented discharges dating back to 1912. Some early constructed wetlands researchers probably began their efforts based on observations of the apparent treatment capacity of natural wetlands. Others saw wastewater as a source of water and nutrients for wetland restoration or creation. Research studies on the use of constructed wetlands for wastewater treatment began in Europe in the 1950's, and in the US in the late 1960's (Kadlec and Knight, 1996).

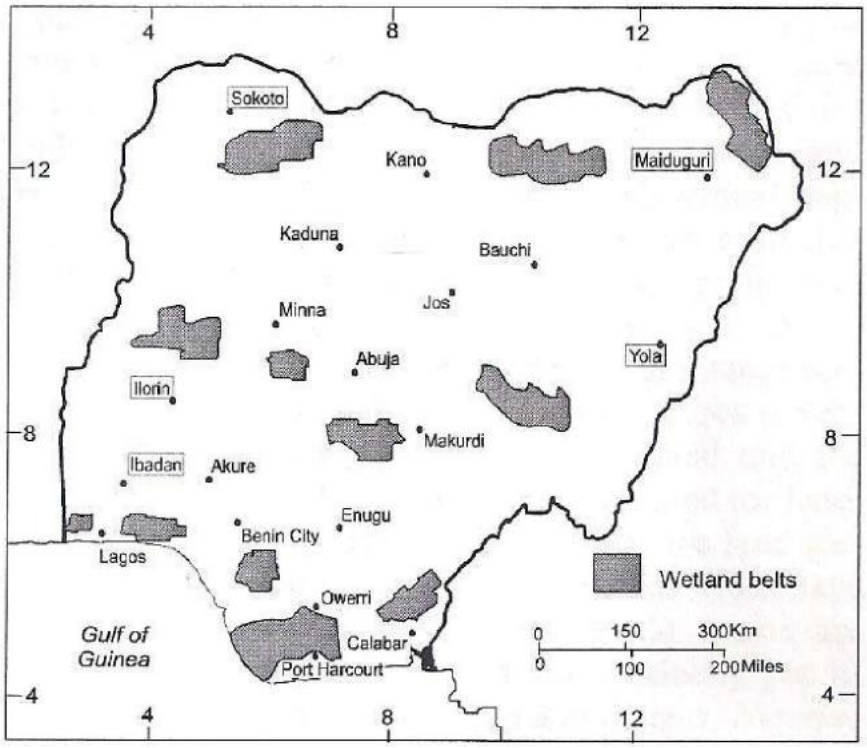
Research efforts in the US increased throughout the 1970's and 1980's, with significant Federal involvement by the Tennessee Valley Authority (TVA) and the U.S. Department of Agriculture in the late 1980's and early 1990's respectively. United States Environmental Protection Agency had a limited role in constructed wetlands research which might explain the dearth of useful, quality-assured data (US EPA., 2000).

2.4.1 History of Wetland in Nigeria

In Nigeria, it has been estimated that wetlands (Figure 2. 1) cover about 3% of the 923, 768 km2 land surface of the country (Uluocha and Okeke, 2004) and fourteen (14) major wetland belts has been identified (Oyebande, *et al*, 2003 and Asibor, 2009). These include: Sokoto-Rima, Komadugu Yobe, Lake Chad, Upper Niger and Kainji Lake, Middle Niger-Lokoja-Jebba-Lower Kaduna, Lower Benue-Makurdi, Cross River, Lower Niger, Niger Delta, Benin-Owena and Okomu, Lagos Lagoon and Lekki Peninsula, Lower Ogun River, Ologe Lagoon, Badagry and Yewa creeks and the trans-boundary wetlands of the Upper Benue.

Nigeria wetland is divided into five categories. The first category is the coastal wetlands found in the southern region bordering the Atlantic Ocean which are the most extensive (Nwankwoala, 2012), the Lagos and Lekki lagoons wetlands, the Niger Delta wetlands and wetland of the Cross River. The second category is the inland riverine wetlands which are scattered across the country including the floodplains of the Niger/Benue, Ogun/Osun, anambra/Imo, Sokoto/Rima, Komadugu Yobe, Ngadda, Yedseram and El Beid Rivers. They are extensively used for livestock grazing, farming, and fishing. The third category is the Lake Chad wetlands which are close to the edge of the Sahara desert and provide water for more than 20 million people living in the region comprising Nigeria, Chad, Cameroon and Niger (Gophen, 2008). The fourth category is the interior wetlands which are not associated with any major river system. Though seasonal, they support a wide variety of livelihood activities including material collection, fishing and farming. The fifth category is artificial impoundment, which includes Kainji lake wetlands which is useful for fisheries and irrigation.

However, the researchers like Oyebande *et al.* (2003) classified all the wetlands in Nigeria into three broad categories namely; freshwater, man-made and saltwater wetland ecosystem.



Source: Uluocha and Okeke (2004)

Fig. 2.1: Map of Nigeria showing Wetland Belts

2.4.2 Types of Wetlands

According to Vymazal and Kropfelova (2008), Constructed wetlands can be classified based on wetland hydrology into free water surface (FWS) and subsurface systems (SF), while based on flow direction into horizontal and vertical for subsurface flow.

Constructed wetlands for wastewater treatment may be classified according to the life form of the dominating macrophyte, into systems with free-floating, floating leaved, rooted emergent and submerged macrophytes (Brix and Schierup, 1989).

According to Vymazal, (2005), Both the free water surface (FWS) wetland and the subsurface flow (SF) wetland utilize emergent aquatic vegetation and are similar in appearance to a marsh. In the horizontal flow systems (HF), the wastewater is fed via an inlet that continues its way under the surface of the bed in a more or less horizontal path

until it reaches the outlet zone. During this passage the wastewater will come in contact with a network of aerobic, anoxic and anaerobic zones. Various types of constructed wetlands may be combined in order to achieve higher treatment effect, especially for nitrogen. Hybrid systems comprise most frequently Vertical flow (VF) and Horizontal flow (HF) systems arranged in a staged manner but, in general, all types of constructed wetlands could be combined in order to achieve more complex treatment efficiency.

2.4.2.1 Free Water Surface Constructed Wetlands

The majority of constructed wetland treatment systems are Surface-Flow or Free-Water surface (SF) systems. These types utilize influent waters that flow across a basin or a channel that supports a variety of vegetation, and water is visible at a relatively shallow depth above the surface of the substrate materials. Substrates are generally native soils and clay or impervious geotechnical materials that prevent seepage. Inlet devices are installed to maximize sheet flow of wastewater through the wetland, to the outflow channel (Reed, *et al.*, 1995). Typically, bed depth is about 0.4 m (WI, 2003).

In the Surface-Flow type of wetland, the impoundment is constructed with an impermeable bottom and sides and the inlet allows polluted water into the pond, diffused from several points through a gravel embankment. This type of constructed wetland closely mimics natural wetlands in terms of vegetation and water flow regime. Vegetation covers most of the water surface, but some areas are left bare to maximize photolytic processes and to provide habitat for birds and access to recreational users of the wetland. Wastewater flows over the soil and through the thicket of vegetation rooted in the soil. Pollutant removal is achieved with sedimentation, filtration, oxidation, reduction, adsorption, and precipitation.

Pollutant concentration decreases linearly or exponentially along the length of the flow path (Water Reuse Research Foundation (WRRF), 2011).

Surface-Flow Wetlands are efficient in removal of organics through microbial degradation and settling of colloidal particles. Suspended solids are effectively removed via settling and filtration through the dense vegetation. Nitrogen is removed primarily through nitrification (in water column) and subsequent denitrification (in the litter layer), and ammonia volatilization under higher pH values caused by algal photosynthesis. Phosphorus retention is usually low because of limited contact of water with soil particles which absorb and/or precipitate phosphorus. Plant uptake represents only temporal storage because the nutrients are released to water after the plant decay (Vymazal *et al.*, 2008).

Constructed wetlands with Surface-Flow are frequently used in North America (Kadlec and Wallace, 2008) and Australia (QDNR, 2000). In Europe, this technology has recently gained more attention, especially in Sweden and Denmark where these systems are used to eliminate nitrogen from diffuse pollution (Vymazal *et al.*, 2006). Besides municipal wastewater, Surface-Flow wetland systems with emergent vegetation have been used to treat various types of wastewaters. Sizing of Surface-Flow wetland systems is usually based either on volume or area. Volume-based methods use a hydraulic retention time to assess the pollutant removal while area-based methods assess pollutant reduction using the overall wetland area (Kadlec and Wallace, 2008).

Kadlec and Wallace (2008), pointed out that Surface-Flow wetland systems are generally not effective for phosphorus removal. This kind of constructed wetlands is particularly

efficient in the pathogens removal, due to the high exposure of the wastewater to the ultra-violet component of the sunlight. For that reason, and also for a good denitrification power, these systems are often used as tertiary treatment (polishing stage) (Kadlec and Knight 1996).

2.4.2.2 Constructed Wetlands with Horizontal Subsurface Flow

According to Vymazal (2001), horizontal flow subsurface constructed wetland systems consist of gravel or rock beds sealed by an impermeable layer and planted with wetland vegetation. The wastetewater is fed at the inlet and flows through the porous medium under the surface of the bed in a more or less horizontal path until it reaches the outlet zone, where it is collected and discharged. The media depth is about 0.6 m deep and the bottom is a clay layer to prevent seepage. Media size for most gravel substrate ranged from 5 to 230 mm with 13 to 76 mm being typical. The bottom of the bed is sloped to minimise water that flows overland. Wastewater flows by gravity horizontally through the root zone of the vegetation about 100-150 mm below the gravel surface. Many macro and micro-organisms inhabit the substrates. The inlet zone has a buried perforated pipe to distribute maximum flow horizontally through the treatment zone. Treated water is collected at outlets at the base of the media, typically 0.3 to 0.6 m below bed surface.

In the filtration beds, pollution is removed by microbial degradation chemical and physical processes in a network of aerobic, anoxic, anaerobic zones with aerobic zones being restricted to the areas adjacent to roots where oxygen leaks to the substrate (Cooper *et al*, 1996 and Vymazal, 2001). This type of constructed wetland was developed in the 1950s in

Germany by Käthe Seidel who designed the horizontal flow subsurface constructed wetland system using coarse materials as the rooting medium (Seidel, 1961).

According to Brix and Schierup (1989), the horizontal flow subsurface constructed wetland system technology was introduced to Denmark and by 1987 nearly 100 soil-based systems were put in operation. Despite problems with surface flow soil-based systems exhibited high treatment effect for organics and suspended solids if reed bed area 3–5 m^2 PE^{-1} (population equivalent) was used (Brix and Schierup, 1989). During the late 1980s, the horizontal flow subsurface constructed wetland systems were also introduced to other countries, such as Austria and United Kingdom (Vymazal and Kröpfelová, 2008). In the 1990s this system spread into most European countries and also to North America, Australia and Asia. In the late 1980s, soil material was replaced by coarse material and at present, washed gravel or rock with grain size of about 10–20 mm are commonly used (Vymazal and Kröpfelová, 2008).

According to Vymazal and Kröpfelová (2008), organic compounds are effectively degraded mainly by microbial degradation under anoxic/anaerobic conditions as the concentration of dissolved oxygen in the filtration beds is very limited. They noted however that suspended solids are retained predominant due to filtration and sedimentation and very high removal efficiency. They noted that the major removal mechanism for nitrogen in horizontal flow subsurface constructed wetland systems is denitrification. But Vymazal, 2007 had noted that removal of ammonia is limited due to lack of oxygen in the filtration bed is a consequence of permanent waterlogged conditions. Phosphorus is removed primarily by

ligand exchange reactions, where phosphate displaces water or hydroxyls from the surface of iron and aluminum hydrous oxides (Vymazal, 2007).

Brix (1994) stated that the most important roles of plants in horizontal flow subsurface constructed wetland systems are provision of substrate (roots and rhizomes) for the growth of attached bacteria, radial oxygen loss (oxygen diffusion from roots to the rhizosphere), nutrient uptake and insulation of the bed surface in cold and temperate regions.

According to Cooper *et al*, (1996), Kadlec and Wallace (2008), the horizontal flow subsurface constructed wetland systems have been designed using either simple "rule of thumb" set at 5 m^2 PE^{-1} or plug-flow first order models. Recently, more complex dynamic, compartmental models have been developed (Langergraber *et al.*, 2009). However, in these models many parameters are difficult to measure and therefore many assumptions must be made. Hence, it is important to realize that more complex models do not necessarily bring more precise design parameters. However, no matter which design model is used, for municipal sewage, the area of horizontal flow subsurface constructed wetland system is usually about 5 m^2 PE^{-1} (Vymazal and Kröpfelová, 2008). Horizontal flow subsurface constructed wetland systems have always been used to treat domestic and municipal wastewaters around the world.

2.4.2.3 Advantages of Subsurfce Flow over Free Water Surface Wetlands

U.S. EPA, (1993) reported that subsurface (SF) constructed wetlands can be a reliable and cost effective treatment method for a variety of wastewaters including domestic, municipal, and industrial wastewaters as well as landfill leachates. Applications range from single

family dwellings, parks, schools, and other public facilities to municipalities and industries. Subsurface (SF) constructed wetlands can be a low-cost, low-energy process requiring minimal operational attention. The concept is particularly well suited for small to moderate sized facilities where suitable land may be available at a reasonable cost. The significant advantages subsurface flow system over surface flow system include lack of odors, lack of mosquitoes and other insect vectors, and minimal risk of public exposure and contact with the water in the system. In addition, accumulation of debris on the surface of the subsurface flow bed offers greater thermal protection in cold climates than the surface flow system type (Reed, 1991).

Due to long retention times the horizontal flow constructed wetland can provide a reliable secondary level of treatment with regard to organic matter (OM) and total suspended solids (TSS). It is well documented that the effectiveness of OM and TSS in horizontal flow constructed wetland varied from 72.0% to 95.0% for suspended solids, 71.2–94.1% for BOD^5 and from 59.7% to 89.0% for COD (Shuib *et al.*, 2011).

2.4.2.4 Hybrid Systems

Different types of constructed wetlands can be combined to achieve greater efficiency in wastewater treatment especially in the nitrogen and pathogen removal. Various wetlands complement each other and because of that there has been a growing trend in building hybrid systems. On the negative side it must be said that those wetlands are more expensive to build and also more complicated to operate than non-hybrid systems (UN-HABITAT, 2008).

A widely used VF-HF design consists of two stages. In the first part several VF beds are installed in parallel to remove organics and provide nitrification. The second stage consists of two or three HF beds in series to further remove solids and nitrogen from the water (Vymazal, 2011). Another popular configuration is the HF-VF system. In order to remove organics and suspended solids and to provide denitrification there is a large HF bed at the beginning. A small VF bed is used to remove the additional organics and suspended solids and also to nitrify ammonia to nitrate (Vymazal, 2011).

2.4.2.5 Comparative Advantages of Constructed Wetlands over Conventional System

According to Kopec (2007), comparative advantages, in particular of the subsurface horizontal flow type, over conventional system include lower operation and maintenance costs, simpler operation and maintenance requirements, robust performance reliability and resistance to flow fluctuation, limits insect breeding and proliferation of vector, and reuse of certain wetland plant species as animal fodder or ornamental flowers to generate income. Kopec (2007) further reported that comparative advantages of the subsurface horizontal flow type, over conventional system include greater removal efficiency of organic pollutants, suspended solids, and helminth eggs, reduced levels of pathogens in the effluent and remaining nutrients rendering the effluent appropriate for crop irrigation, lower odor emissions, attractive treatment plant and creates a habitat for wildlife.

2.4.2.6 Limitation of Constructed Wetlands

Researchers USDA (1995), ITRC (2003), highlighted in their studies certain limitations to

the use of constructed wetlands in treating wastewater as compared with conventional wastewater treatment systems which include larger land areas requirement, relatively slow to provide treatment, performance may be less consistent, reduced efficiencies during colder seasons, surges in flow or pollutants may temporarily reduce treatment effectiveness, tolerance of temporary water level drawdown, but not complete drying, providing breeding grounds for mosquitoes and other pests, anaerobic conditions might produce disagreeable odors associated with natural biological functions, long-term maintenance may be required, the biological components are sensitive to toxic chemicals, and contaminant accumulation must be monitored to maintain ecological health of the system.

2.5 Treatment Processes

The design of wetland is based on the use of permeable substrata such as gravel, commonly planted with emergent wetland plants such as Typha, Schoenoplectus, Phragmites and Cyperus. The effluent percolates through the gravel, providing more contact to the plant roots and rhizomes and exposure to oxygenated conditions in the rhizosphere (Haberl *et al*, 2003; Schro der *et al*, 2007).

However, the presence of toxic compounds in effluent affects plant growth and remediation efficiency of wetland system (Kabra *et al*, 2012; Khandare *et al*, 2013). The researchers Mojiri *et al*, (2013) noted that typha genus is one of the most widely used plant in constructed wetlands.

This plant has dense and extensive root system which spread and grows even under harsh conditions. It maintains the contaminant removal efficiency of the wetland and provides oxygen for aerobic degradation of organic pollutants in the rhizosphere (Li *et al.*, 2010).

Endophytic bacteria inhabit the interior tissues of the plant without causing pathogenicity to their host (Sessitsch *et al.*, 2013). Wetland Plants offer nutrients and residency to endophytic bacteria. In response, endophytic bacteria improve plant health and growth due to plant growth-promoting activities. Moreover, endophytic bacteria reduce both the toxicity and evapotranspiration of organic pollutants due to their pollutant-degrading potential (Khan *et al.*, 2004).

According to Sessitsch *et al.*, (2013) and Weyens *et al.*, (2009), "many studies revealed that endophytic bacteria enhance plant growth and cleanup of soil and water contaminated with different organic and inorganic pollutants. Best use of constructed wetlands is as the final step in an overall treatment train that includes primary and secondary pretreatment. Thus, constructed wetlands can provide the near-final step for producing an effluent that can meet advanced water treatment (AWT) standards".

2.5.1 Influence of Macrophyte on Pollutant Bioconversion and Removal in Treatment Wetlands

The biogeochemical cycling and storage of nutrients, organic compounds, and metals in natural wetlands is mimicked in constructed wetlands, through the use of plants, porous media and associated microorganisms (Hunter *et al.*, 2001; Sonavane *et al.*, 2008). The presence of emergent macrophytes is one of the most conspicuous features of constructed wetlands and their presence distinguishes constructed wetlands from unplanted soil filters or lagoons (Greenway, 2007; Vymazal, 2011). Their positive role on the performance of constructed wetlands has been well established in numerous studies measuring treatment with and without plants (Akratos and Tsihrintzis, 2007; Yang *et al.*, 2007; Brisson and

Chazarenc, 2009; Kadlec and Wallace, 2009). Generally, the performance of wetlands for wastewater treatment depends on the growth potential and ability of macrophytes to develop sufficient root systems for microbial attachment and material transformations, and to incorporate nutrients into plant biomass that can be subsequently harvested for nutrient removal (Kyambadde *et al.*, 2004; Vymazal and Kröpfelová, 2009). However, empirical exploitation of plants is a common practice. Availability, expected water quality, normal and extreme water depths, climate and latitude, maintenance requirements and project goals are among the variables that determine the selection of plant species for constructed wetlands (Stottmeister *et al.*, 2003). While there is a recognition that the improvement of water quality in treatment wetland applications is primarily due to microbial activity (Faulwetter *et al*, 2009; Kadlec and Wallace, 2009), experience has shown that wetland systems with vegetation or macrophytes has a higher efficiency of water quality improvement than those without plants (Coleman *et al.*, 2001; Tanner, 2001; Brisson and Chazarenc, 2009). The emphasis of constructed wetland technology to date has been on soft tissue emergent plants including *Cyperus papyrus*, *Phragmites*, *Typha* and *Schoenoplectus* (Okurut, 2000; Kadlec and Wallace, 2009). These are fast growing species that have lower lignin contents and are adaptable to variable water depths. The productivity of emergent macrophytes is the highest among the aquatic plant communities in the tropics as well as in temperate regions. Emergent macrophytes are characterized by a photosynthetic aerial part above the water surface and a basal part rooted in the water substrate.

Emergent macrophytes find application in both surface and subsurface flow configurations of constructed wetlands. Macrophytes, in addition to their site specific roles (i.e. attenuation of light, water current and wind velocity, aesthetic appearance, etc) are essential

in the wetland treatment systems because they have properties that foster many wastewater treatment processes (Kyambadde and Dalhammar, 2005; Kadlec and Wallace, 2009). Aquatic plants can absorb inorganic (nutrients, metals, etc), and organic pollutants (aromatics, hydrocarbons, etc) from wastewater and incorporate them into their own structure (Haberl *et al.*, 2003), thus providing a storage and a release of nutrients through the plant growth cycle (NAS-NRC, 1976; Shetty, 2005). They create favorable conditions for microbes that contribute to the processing of pollutants by influencing the oxygen supply to the water, providing attachment surfaces, providing carbon and electron donor via carbon content of litter and root exudates (Brix and Schierup, 1989; Kadlec and Wallace, 2009). Further, aquatic plants promote stable residual accretions in the wetland (Greenway, 2007; Vymazal, 2007). These residuals contain pollutants as part of their structure or in absorbed form, and hence represent a burial process of contaminants (Kadlec and Wallace, 2009). These facts have been exploited in constructed wetland systems which have been widely used during the past decades for the treatment of wastewater because of their good efficacy to improve water quality at low operational costs (Vymazal, 1999; Neralla *et al.*, 2000; Rousseau *et al*, 2004; Molle *et al.*, 2005 ; Zurita *et al*, 2008; Perbangkhem and Polprasert, 2010).

The natural wetlands too have been shown to have potential as sink and buffering site for organic and inorganic pollutants (Buchberger and Shaw, 1995; Muthuri and Jones, 1997; Mannino *et al.*, 2008; Sekomo, 2010).Wetland vegetation occasion evapotranspiration, and a corresponding increase in the hydraulic retention time that can be explained by a net biomass productivity accompanied by transpiration (Kansiime and Nalubega, 1999; Kyambadde *et al.*, 2005). Emergent macrophyte vegetation tends to increase rates of water

loss through evapotranspiration when compared to rates of evaporation from bodies of open water (Jones and Humphries, 2002). At present there is no clear evidence that treatment performance is superior or different between the common emergent wetland species used in treatment wetlands (IWA, 2000; Zhu *et al.*, 2010). Even so some soft tissue emergent macrophytes including *Phragmites* sp.,*Schoenoplectus* sp., *Typha* sp. and *Carex* (true sedge) are well known for their potentials in constructed wetlands treating wastewater and fecal sludge, and their performances are well documented, especially for the high latitudes, temperate climate regions (Fennessy *et al.*, 1994; Coleman *et al*, 2001; Ciria *et al.*, 2005; Stein *et al.*, 2006). These macrophytes are, however, not found in all regions of the world and efforts are being made worldwide to select candidate macrophytes to be exploited locally in constructed wetlands (Azza, 2000; Yang *et al.*, 2007; Brisson and Chazarenc, 2009; Huang, 2010; Perbangkhem and Polprasert, 2010).

2.5.2 Biological Oxygen Demand ($BOD_{5)}$ Removal

According to USEPA (1993), the physical removal of BOD_5 is believed to occur rapidly through settling and entrapment of particulate matter in the void spaces in the gravel or rock media. Soluble BOD_5 is removed by the microbial growth on the media surfaces and attached to the plant roots and rhizomes penetrating the bed. Some oxygen is believed to be available at micro sites on the surfaces of the plant roots, but the remainder of the bed can be expected to be anaerobic. The systems can never achieve complete BOD_5 removal and a residual BOD_5 from 2 to 7 mg/L is typically present in the effluent due to the decomposition of plant litter and other naturally occurring organic materials.

2.5.3 Nitrogen Removal

The removal of non-ionized ammonia is typically the major nitrogen parameter of concern due to its toxicity for fish and other aquatic animals, and to its added oxygen demand on receiving streams. Many of the earliest SF wetland systems were only required to remove BOD_5 and TSS and have done so successfully (Gersberg *et al.*, 1985).

The dominant forms of nitrogen (N) in wetlands which are important to wastewater treatment include organic nitrogen, ammonia, ammonium, nitrate, nitrite, and nitrogen gases. Inorganic forms are essential to plant growth in aquatic systems but if the amount limited it can affect plant productivity. The nitrogen entering wetland systems can be measured as organic nitrogen, ammonia, nitrate and nitrite. Ammonia is oxidized to nitrate by nitrifying bacteria in aerobic zones which typically occurs at the above soil level. The oxygen required for nitrification is supplied by transmission from the atmosphere and leakage from macrophyte roots. Organic N is mineralized to ammonia by hydrolysis and bacteria degradation. Nitrates are then converted to nitrogen gas (N_2) and nitrous oxide (N_2O) by denitrifying bacteria in anoxic and anaerobic zones which usually occur in limited oxygen supply (Koottatep, 2009). Nitrogen is also taken up by plants, incorporated into the biomass and released back as organic nitrogen after decomposition.

Other removal mechanisms include volatilization and adsorption. Typically, these mechanisms are generally of less importance than nitrification - denitrification, but they can be seasonally important (Kadlec and Knight, 1996).

In 1999, researchers at the Gist-Brocades in Delft, Netherlands discovered a new reaction to be added in the nitrogen cycle which is called Annamox (anaerobic ammonia oxidation) Reaction. More recently, Wendong and Jing (2009) found that integration of partial

nitrification and anaerobic ammonium oxidation (Annamox) in constructed wetlands creates a sustainable design for nitrogen removal. The previous observations of high ammonia removal in constructed wetlands under anaerobic and low-oxygen conditions were attributed to partial nitrification (conversion of ammonium to nitrite, or nitritation) and Anammox, in addition to nitrification and denitrification (Chiemchaisri *et al.*, 2009, and Wendong and Jing, 2009).

Nitrifiers and Anammox bacteria may be natural partners in many oxygen-limited situations (Schmidt *et al.*, 1996). At the concentrations of dissolved oxygen in the ,subsurface flow wetlands, nitritation and nitrification could take place in the bulk water, while Anammox could occur in the deep layer of bio-films developed from gravel media in wetlands. Ammonia that removed will be converted to nitrite and nitrate. Mass balance analysis for nitrate plus nitrite, confirms that nitritation, nitrification and Anammox were responsible for nitrogen removal in the subsurface flow wetlands (Wendong and Jing, 2008).

Completely autotrophic nitrogen-removal over nitrite (CANON) is closely related to Anammox process in which ammonium is first partially oxidized to nitrite, then transformed with remaining ammonium into dinitrogen by planctomycetelike bacteria growing in anaerobic zones in treatment system (Guangzhi, 2007). Unlike the Anammox process, CANON can occur in a single stage aerobic system. Considering that wetland contains a network of intermeshing aerobic, anoxic, and anaerobic zones within the same system, it provides an ideal habitat for the coexistence of different microbial communities. However, many of the earliest constructed wetlands were only required to remove BOD

and total suspended solid (TSS). In some cases, their permits have since been revised to require the ammonia removal (Koottatep and Polprasert, 1997).

Many of these new systems also have ammonia limits depending on receiving water requirements. The limiting factor in ammonia removal via nitrification is believed to be the availability of oxygen in the media profile. Some study found that the excellent ammonia removal is based on plant roots (which typically abundance of oxygen) throughout the profile, and sufficient hydraulic retention time (HRT) to complete the reactions (Konnerup *et al.*, 2009; Brix *et al.*, 2007).

However, there is no consensus on how much oxygen can be furnished by the vegetation in SFCW or on the oxygen transfer efficiency of various plant species. Sim (2003) demonstrated that the surface area must be large enough to secure a sufficient oxygen transfer to cover the need for microbial degradation of organic matter and nitrification of ammonium. Sim (2003) also found that the removal efficiencies of N decreased when the system operated with high hydraulic loading rate (HLR).

2.5.4 Phosphorus Removal

Phosphorus removal in most constructed wetland systems is not very effective because of the limited contact opportunities between the wastewater and the soil. Plants take up some of the phosphorus and return it to the bottom sediments as they die (USEPA, 1993).

The removal of phosphorus is important since it is known to be major limiting nutrient for algae growth in freshwater ecosystems (Wetzel, 2001). Wetlands remove phosphorus through biological, chemical and physical processes. Sediment burial is considered to be the major long-term phosphorus storage in wetlands (Reddy *et al.*, 1999). However, part of the sediment organic phosphorus can be mineralized to dissolved inorganic phosphorus,

which can subsequently be partially released back to water (D'Angelo and Reddy, 1994; McLatchey and Reddy, 1998).

The major processes responsible for phosphorus removal in SFWC are typically by adsorption, precipitation and plant up-take rates. The frequent filtration materials used in SFCW is gravel, which is commonly good in absorption compared to the plant roots (Vymazal, 2004). Phosphorus is an important nutrient required for plant growth and usually acts as a limiting factor for vegetative productivity. Phosphorus is transformed in the wetland by a complicated biogeochemical cycle. Accordingly, most of the researcher claimed that wetlands are not efficient in phosphorus reduction (Kadlec and Knight, 1996).

However, wetlands are not long-term removal solution for phosphorus as compared to nitrogen. In the past, if the systems operate in a longer periods (maximum of 9 years) the phosphorus removal will decrease over the years probably because of limited sorption capacity. The amount of phosphorus removed is not more than 5% of the total removed phosphorus in the beginning of wetland operation. As the sorption decreases over the years and macrophyte biomass increases simultaneously, the phosphorus bound in biomass becomes higher but it rarely exceeds the level of 20% of the total phosphorus removed (Binhe, 2008; Richardson and Qian, 1999).

Phosphorus removal in most constructed wetland systems is also not very effective because of the limited contact between the contaminant in wastewater and the soil. Some experiment and developmental work has been undertaken using expanded clay aggregates and the addition of iron and aluminium oxides. Some of these treatments are promisingly but the long-term expectations have not been observed so far (Vymazal, 2004). Some systems uses sand instead of gravel to increase the phosphorus retention capacity, but selecting this media would reduce the hydraulic conductivity of sand compared to gravel.

Therefore, a wide land area is required in order to remove the phosphorus (U.S. EPA, 1993).

2.5.6 Heavy metal removal

Heavy metals is a collective name given to all metals above calcium in the Periodic Table of Elements, which can be highly toxic, and which have densities greater that 5g/cm^3 (Skidmore and Firth, 1983).

The main heavy metals of concern in freshwater include lead, copper, zinc, chromium, mercury, cadmium and arsenic. The main wetland processes that remove heavy metals namely, binding to soils, sedimentation and particulate matter, precipitation as insoluble salts, and uptake by bacteria, algae and plants (Kadlec and Knight, 1996). These processes are very effective, with removal rates reported up to 99%. A range of heavy metals, pathogens, inorganic and organic compounds present in wetlands can be toxic to biota. The response of biota depends on the toxin concentration and the tolerance of organisms to a particular toxin. Wetlands have a buffering capacity for toxins, and various processes dilute and break down the toxins to some degree (Reed *et al.*, 1995).

Metals are accumulated in the sediments and removed from the water column. But, they remain within the wetland and are stored there indefinitely. While some metals are adsorbed on the sediment exchange sites, this process is not sustained. Plant uptake of metals can remove some of the metals if the plant material is harvested and removed from the wetland. Usually, when the plant material decomposes, the up taken metals return to the wetland sediments (Ali *et al.*, 2013).

2.5.7 Organic Compound Removal

Many classes of hydrocarbons are removed, to varying extents, in wetlands. These include fuels, oils, aliphatic and aromatic hydrocarbons, halogenated hydrocarbons, oxygenated hydrocarbons, volatile organic compounds, herbicides, and insecticides. The dominant removal mechanisms include volatilization, photochemical oxidation, sedimentation, sorption, and biological degradation (WRFF, 2011).

2.6 First-Order Kinetics

Mara, (2004), reported that biochemical oxygen demand (BOD) removal often approximates first-order kinetics. This reaction is expressed mathematically as equation (2.1).

$$\frac{dL}{dt} = -K_1 L \qquad (2.1)$$

Where L is the amount of BOD remaining at time t; and K_1 is the first-order rate constant for BOD removal; the differential coefficient $\frac{dL}{dt}$ is the rate at which the organic matter is oxidized, and the minus sign indicates a decrease in the value of L with time.

Equation (2.1) is the differential form of the first-order equation for BOD removal; it can be integrated to equation. (2.2) as:

$$L = L_0 e^{-k_1 t} \qquad (2.2)$$

Where L_0 is the value of L at t = 0.

L_0 is the amount of BOD in the system before oxidation occurs; it is therefore the ultimate

BOD. The amount of BOD removed or 'satisfied' (= organic matter oxidized) plus the amount of BOD remaining (= organic matter yet to be oxidized) at any time must obviously equal the ultimate BOD (= initial amount of organic matter). This is expressed in equation (2.3):

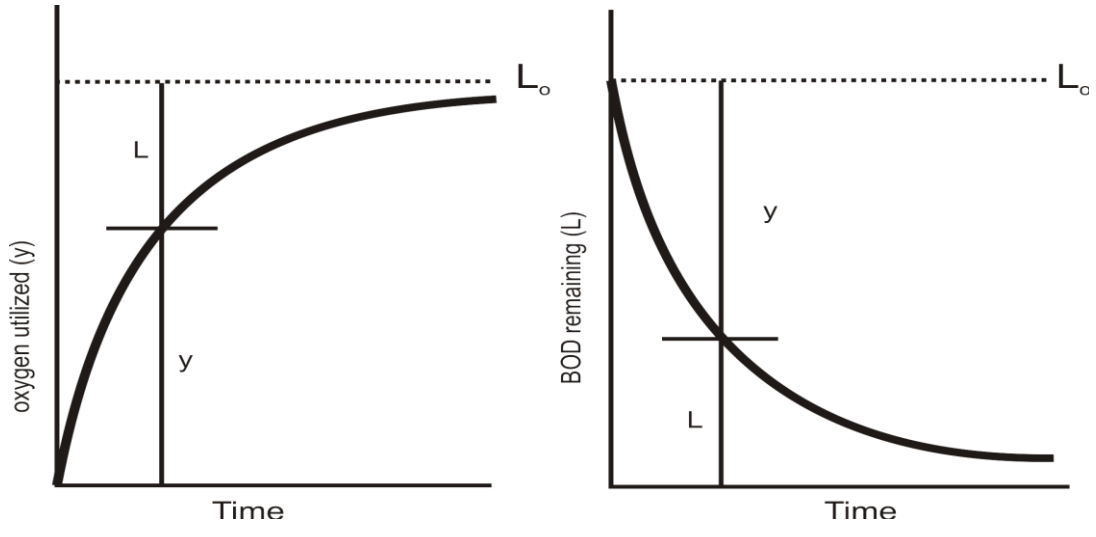
$$y = L_0 - L \tag{2.3}$$

Where y is the BOD removed at time t.

Substitution of equation (2.3) into equation (2.2) yields equation. (2.4):

$$y = L_0(1 - e^{-k_1 t}) \tag{2.4}$$

Generalized BOD curves (plots of equations (2.2) and (2.4) are shown in Figure (2.1), from which the relationship between y, L and L_0 is readily seen. Biochemical Oxygen Demand Removal Kinetics is illustrated in Fig. 2.2.



(a) (b)

Figure 2.2: Generalized BOD Curves

Equation (2.2) can also be written as:

$$L = L_0 10^{-K_1 t} \quad (2.5)$$

Where, $K_1 = {}^{k_1}/_{2.3}$. Because of the confusion that generally arises between K_1 and k_1, it is best to give the base when quoting k_1 values – for example 0.23 day^{-1} (base e) or 0.10 day^{-1} (base 10).

2.6.1 Temperature

The rate constant k_1 is a gross measure of bacterial activity and, in common with almost all parameters describing microbiological growth processes; its value is strongly temperature dependent. Its variation with temperature is usually described by an Arrhenius equation of the form:

$$k_{1(T)} = k_{1(20)} \varphi^{T-20} \quad (2.6)$$

where $k_{1(T)}$ and $k_{1(20)}$ are the values of k_1 at T°C and 20°C, respectively, and φ is an Arrhenius constant whose value is usually between 1.01 and 1.09.

2.6.2 Continuous Flow Processes

According to Mara, (2004), equations (2.2) and (2.4) describe the bio-oxidation of a given quantity of organic matter to which no further addition of organic matter is made. They represent conditions in a 'batch' oxidation process. However, wastewater treatment plants operate with a continuous inflow of raw wastewater and a continuous outflow of treated effluent. The quantity of BOD removed in bacterial oxidation is given by equation (2.1) as

k_1L g/m^3 day where L is the BOD of the reactor contents. Under this condition the BOD of the reactor contents is L_e, Q is the flow in m^3/day and L_i is the influent (mg/L). If V is the working volume of the reactor in m^3, then:

$$L_iQ = L_eQ + k_1LV_e \quad (2.7)$$

Re-arrangement:

$$L_\theta/L_i = \frac{1}{1+k_1(V/Q)} \quad (2.8)$$

The ratio V/Q is the mean hydraulic retention time (θ, days), the average length of time a typical 'packet' of wastewater may be expected to remain in the reactor before being discharged in the effluent flow. Equation (2.8) can therefore be written as:

$$L_\theta/L_i = \frac{1}{1+k_1\theta} \quad (2.9)$$

2.6.3 Hydraulic Flow Regimes

The flow of wastewater through a microbiological reactor can approximate either complete mixing or plug flow. These two flow patterns represent two extreme or ideal conditions. In practice the hydraulic regime lies between these two extremes and is described as 'dispersed flow'.

2.6.4 Complete mixing

The influent to this ideal reactor is completely and instantaneously mixed with the reactor contents, which are, as a result of the intense mixing, uniform in composition throughout. The effluent is identical, therefore, in every respect to the reactor contents. The removal of

BOD is described by equation (2.7).

2.6.5 Plug flow

The concept of plug flow may be readily grasped by imagining the wastewater, on arrival at the reactor, to be placed in watertight 'packets' which then travel along the length of the reactor – as if on a conveyor belt – with no transfer of material from one packet to another, but with complete mixing within each packet. Since each packet receives no additional BOD and loses none to a neighbouring packet, the removal of BOD within each packet is essentially a batch process, so that BOD removal in a plug flow reactor follows equation (2.2). It is, however, convenient to adopt the notation used in equation (2.7) and rewrite equation (2.2) as:

$$L_\theta = L_i e^{-k_1 \theta} \tag{2.10}$$

The principle of the design for CWs subsurface flow (SSF) systems is based on an assumption of plug flow movement of water through the wetland with first-order reaction kinetics primarily by biological degradation. As an attached biological reactor involving microbes, modeling CWs typically combines biological degradation and system hydraulics. The basic relationship which has been used to simultaneously describe the two components mentioned above is given:

$$C_e = C_i e^{-KT} \tag{2.11}$$

Where C_e (mg/ L) is effluent concentration,

C_i (mg/ L) influent concentration,

K (1/days) is a temperature dependent first order reaction rate constant and T (days)

are hydraulic residence time.

The principle of the design for horizontal flow (HF) SSF systems is based on Equation 2.10, originally proposed by Kickuth (1977) as:

$$A = Q_d(\ln C_i - \ln C_0)/K_{BOD} \quad (2.12)$$

Where A = the surface area of the bed, (m^2)

2.6.6 Removal Mechanisms

Wetland systems reduce many contaminants, including organics BOD, COD, suspended solids, nitrogen, phosphorus, trace metals, and pathogens. According to Vymazal (2001), this reduction may be accomplished by diverse treatment mechanisms including sedimentation (gravitational settling of solids), filtration (particulates filtered mechanically as water passes through substrate, root masses or fish), adsorption (Inter-particle attractive force – van der Waals force), volatilisation (volatilisation of NH_3 from the wastewater), chemical precipitation (formation or co-precipitation with insoluble compounds), chemical adsorption (adsorption onto substrate and plant surface), chemical decomposition (decomposition or alteration of less stable compounds by phenomena such as UV irradiation, oxidation and reduction), bacterial metabolism (removal of colloidal solids and soluble organics by suspended, benthic, and plant supported bacteria), plant metabolism, plant absorption (under proper conditions significant quantities of Nitrogen, Phosphorus, Heavy Metals or Refractory Organics will be taken up by plants), and natural die-off (natural decay of organisms in an unfavorable environment).

2.6.7 Microorganism

According to Wetzel, (1993), a fundamental characteristic of wetlands is that their functions are largely regulated by microorganisms and their metabolism. Some microbial transformations are aerobic while others are anaerobic. Microbial populations adjust to changes in the water delivered to them and can expand quickly when presented with suitable energy-containing materials. When environmental conditions are no longer suitable, many microorganisms become dormant and can remain dormant for years. The microbial community of a constructed wetland can be affected by toxic substances, such as pesticides and heavy metals, and care must be taken to prevent introduction of such chemicals at damaging concentrations (Hilton 1993).

2.6.8 Animals

Constructed wetlands provide habitat for a rich diversity of invertebrates and vertebrates. Invertebrate animals, such as insects and worms contribute to the treatment process by fragmenting detritus and consuming organic matter. The larvae of many insects are aquatic and consume significant amounts of material during their larval stages, which may last for several years. Invertebrates also fill a number of ecological roles. For instance, dragonfly nymphs are important predators of mosquito larvae. Although invertebrates are the most important animals as far as water quality improvement is concerned, constructed wetlands also attract a variety of amphibians, turtles, birds, and mammals (USDA, 1995).

2.6.9 Plants

Wetland vegetations (plants) are the most important component in the wetland system. It has been widely demonstrated that plants are involved in almost every function within

wetland systems (Brix, 1997). One of the most important mechanisms for pollutant removal in wetlands is by biological means (Reddy and De-Busk, 1987), in which plants play a partial role. Plants can be involved, either directly or indirectly, in the removal of pollutants from wastewater. When plants directly uptake contaminants into their root structures, this process is called phytodegradation (Phytoextraction). When plants produce substances that add to biological degradation, this process is called rhizodegradation. The process by which contaminants enter the plant biomass and are transpired through the plant leaves is called phytovolatization (ITRC, 2003). Wetland plants take up macro-nutrients (Such as N and P) and micro-nutrients through their roots during active plant growth. At the beginning of plant senescence most of the nutrients are translocated to the rhizomes and roots (Mitsch and Gosselink, 2000).

According to Yang *et al.*, 2006, Huett *et al.*, (2005), vegetated treatment wetlands are more efficient at removing BOD, SS, nitrogen, and phosphorus than unvegetated wetlands Specifically, aquatic plants in treatment wetlands act as physical filters (Hammer, 1989, Brix, 1994), take up nutrients and other constituents (Greenway, 2007, Lin *et al.*, 2002), provide a substrate for microbiota and microinvertebtares (Kadlec and Knight, 1996, and Wetzel, 2000), contribute carbon and create anaerobic zones for denitrification (Stefan *et al.*, 1994, Reed *et al.*, 1995), add oxygen to sediment zones where nitrification occur and enhance denitrification by pulling nitrates from the water column into anaerobic zones within the sediments as the roots actively absorb water needed for transpiration (Martin *et al.*, 2003).

Aquatic plants have both structural and physiological adaptations to water logging, which allows them to tolerate anoxia in saturated substrates (Mitsch and Gosselink, 2000). Plants

capacity to supply oxygen to the root zone and nutrient uptake varies among species due to the difference in vascular tissue, metabolism and root distribution (Gersberg *et al.*, 1986a; Jackson and Armstrong, 1999). According to Joseph, (2005), the depth of the bed should not exceed the potential root development zone for the selected plant species. In addition, apart from providing attachment sites and diffusible oxygen to bacteria, root-mats increase wastewater residence time and retention of suspended organic particles, which upon degradation provide nutrients to bacteria and plants.

Numerous studies have confirmed that water treatment is improved in vegetated systems compared to systems containing no plants. However, most of these studies were done when the vegetation was new and actively growing, absorbing abundant amounts of nutrients, minerals and waters as the plant transpired and produced large amounts of biomass (Baskar *et al.*, 2014).

2.6.10 Design considerations

USDA, (1995), report that the performance of many systems monitored, has varied due to influences of the diverse factors that affect performance, such as location, type of wastewater, wetland design, climate, weather, disturbance, and daily or seasonal variability. However, Mitsch (1992), suggested guidelines for creating successful constructed wetlands which include keeping the design simple with minimal maintenance, using natural energies, designing the wetland with the landscape and for the extremes of weather and climate, mimicking the natural systems, and giving the system time because wetlands do not necessarily become functional overnight.

2.7 Site Selection

According Mitsch (1992), selection of a site for a constructed wetland is greatly influenced by proximity of the source of wastewater, surface topography that allows water to flow through the system by gravity, compactable soil to minimize seepage to groundwater, the closeness of water table, prone to flood, existence of threatened or endangered species and archaeological or historic resources.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials

The materials used in this research for the construction of a pilot-scale horizontal flow subsurface wetland system are:

i. Water, sand, gravel for construction of the wetland cell.

ii. Hand tools: Digger, shovel, head pan, hacksaw, hammer, rope, plumb, angular square and steel tape.

iii. Gravel of different sizes (10-30mm) substrates for inlet and outlet zones to prevent clogging, and (1-10mm) as substrate.

iv. Valves for control of wastewater flow through the wetland

v. Polyvinyl chloride (PVC) pipes and fittings (bends, elbows, sockets, tees, unions, plugs) for connecting the various units of the wetland.

vi. Wastewater from ABU waste stabilization ponds

vii. Canna indica (*Cannaceae*), Common reed, Phragmites karka, *(Poaceae*) and Typha australis, Cattail (*Typhaceace)* as aquatic plants or vegetation for the wetland cells.

3.1.1Apparatus, Instruments, Equipment and Reagents

The apparatus, instruments, equipment and reagents used during the experimentation include conical flasks (Pyrex, England), BOD bottles (Wheaton, USA), pipettes (Technico BS, 700), burettes (Pyrex, England), beakers (Kimax, USA), condensers, reflux flasks (Gallenkamp, England, incubator (Raven Britain), thermometer (Wegtech), pH meter

(model pHS-2S, Rex- China), funnels (Labplex, England), Atomic Absorption Spectrophotometer (AAS) machine, refrigerator (Thermocool HRF-300N), weighing balance (Chyo, Japan), water bath (Gallenhamp, England), oven (Sheffield England), desiccators (Monax, Scotland), petri-dishes (Pyrex, England), measuring cylinder (Kimax, USA), filter paper (Whitman, qualitative circles), Nesslers reagents (East Anglia Chemical), Silver nitrate (Griffin and George, England), Potassium chromate (AnoloR, BDH Chemical Ltd England), Ferrous ammonium sulphate (M&B Laboratory Chemical England), Silver sulphate (Kem Light Laboratory Ltd), Potassium dichromate (M&B Laboratory Chemical England), Methyl orange (AnoloR, BDH Chemical Ltd England), Sulphuric acid (AnoloR, BDH Chemical Ltd England), Phenolphthalein (AnoloR, BDH Chemical Ltd England), Sodium thio-sulphate (M&B Laboratory Chemical England),, Starch solution Fiscons Scientific Apparatus and M&B Laboratory Chemicals, England), Alkali-iodide azide (made up of NaOH, Sodium Iodine and Sodium Azide; Avondole Laboratories, England; BDH Chemicals Ltd, England; Laboratory Technology Chemicals, Avishkar respectively) Manganese sulphate (M&B Laboratory Chemicals, England), and distilled water (Water Still Aquation/A4000)

3.2 Research Method

3.2.1 Sources of Data

Both primary and secondary data were used to execute this research. However, primary data served as the main source of data from which the analyses were drawn.

3.2.2 Primary Data

The primary data were the results of field measurements and laboratory tests on

wastewater samples collected before and after passing through the constructed wetland cell.

3.2.3 Secondary Data

The secondary data were collected from government agencies through interviews, textbooks, journals, magazines, internet and papers presented at different seminars and other scholarly gatherings or fora. The secondary data were also collected from Ahmadu Bello University Library, British Council Library, National Library, and National Water Resources Library, Kaduna.

3.2.4 Design of the Constructed Wetland

This section comprises the design stage which has been subdivided into A-G. The design stage involving a desk study of available literature and records, field measurements and laboratory testing and calculation of wetland parameters took six weeks.

(A) Sizing of the Constructed Wetland

In calculating the size of the constructed wetland cell the following parameters were pre-determined:

1. The depth of the wetland cell, 45cm,
2. Maximum monthly average ambient temperature (T) of Zaria, 23 ^{0}C,
3. Desired effluent BOD concentration of constructed wetland, 20mg/l.

(B) Calculation of Reaction Rate Constant for BOD at Appropriate Temperature

The reaction rate constant K_T (day-$^{-1}$) for BOD at the appropriate temperature is calculated using Crites and Tchnobanoglous, 1998 formula:

$K_{T=} k_{20} (1.06^{(T-20)})$

$$K_T = k_{20}(1.06^{T-20})$$

Where, K_{20} = rate constant at 20 ^{0}C,

T = operational temperature of (d^{-1}) system, ^{0}C,

K_{20} = rate constant at 20 ^{0}C.

The reaction rate constant at 20^{0}C (k_{20}) varies depending on the system. The researchers Crites and Tchnobaglous (1998) estimated K_{20} to be 1.1 day^{-1} for sewage water. Thus, 1.1 day^{-1} is assumed.

The

$$K_T = k_{20}(1.06^{T-20})$$

$= 1.1 (1.06)^{23-20}$

$= 1.310$

$K_{BOD} = K_T d \eta$

$$K_{BOD} = K_T d \eta$$

Where d = depth of water column, m,

η = porosity of the substrate medium (% expressed as (fraction),

K_{BOD} = 1.310 x 0.45 x 0.356

= 0.210 m/day

(C) Detention Time t (Day)

$T = - \ln (C_e/C_i)/ K_T$

$T = -\ln(C_e/C_i)/ K_T$

= - ln (20/110)

= 1.30 day

Where C_i = BOD concentration of water entering the system (mg/L) or (g/m^3), and

C_e = BOD concentration of desired or goal.

(D) Organic Loading Rate (L_{org})

$$Lorg = \frac{cdw\eta}{t}$$

Where c = influent BOD concentration, mg/L,

d_w = wetland depth, m,

η = porosity, (%).

Lorg = 110 x 0.45 x 0.356

= 17.622 g BOD/m^2-day

(E) Calculation of the Area of the Wetland

Area of the wetland (A) is calculated by using the formula of Kickuth (1977) in which,

$$A = Q_d (\ln C_i - \ln C_e)/K_{BOD}$$

$$A = Q_d (\ln C_i - \ln C_e)/K_{BOD}$$

Where A = Surface area of bed, m^2,

Q_d = Average daily flow rate of sewage, m^3/day,

C_i = Influent BOD_5 concentration sewage, m^3/day,

C_e = Effluent BOD_5 concentration, mg/l,

K_{BOD} = Rate constant (m/d) and K_{BOD} is determined from the expression $K_T$dn.

It is assumed that the constructed wetland will serve a housing estate of 50 persons. The sizing of the constructed wetland with wastewater flow of 120 liters per day can be determined as follows:

$$A = Q_d (\ln C_i - \ln C_e)/K_{BOD}$$

$$A = Q_d (\ln C_i - \ln C_e)/K_{BOD}$$

Where, Q_d = 50 x 120 /1000 = 6 m^3/day.

Then A = 6 (ln 110 – ln 20)/0.210

= 48.68 m^2

(F) Width of Wetland Cell (W),

According to Miller and Black (1985), a long length-width ratio is required to ensure plug flow hydraulics and this is given as:

$$W = (A_s/R_A)^{1/2}$$

Where A_s = Area of the wetland cell, m^2

R_A = Ratio of the Length and the width of the wetland (4:1)

$W = (48.68/4)^{1/2}$

W =3.5 m,

(G) Length of the Wetland Cell (L)

In accordance with USEPA (1988), the effective length of constructed wetland can be calculated as:

$$L = A/W$$

= 48.68/3.5

= 14 m

3.2.5 Experimental Site Start-up

The constructed wetland was built based on the results obtained in treatment plant design and its construction stage took twenty-six (26) weeks. A pilot scale wetland system was designed and constructed adjacent to the Ahmadu Bello University waste stabilization pond. The dimensions of the constructed wastewater subsurface flow cell are 14m x 3.5m x 0.45m; the bottom slope is 1%. The excavated cell was lined with geomembrane of polyethylene to prevent percolation of wastewater into the groundwater. The base of cell was filled with gravel of 10-15mm size to the depth of 0.2m, followed by sand layer of 0.3-0.5mm size to the depth of 0.20m depth and then covered with 0.05m local soil (Fig.3.1).

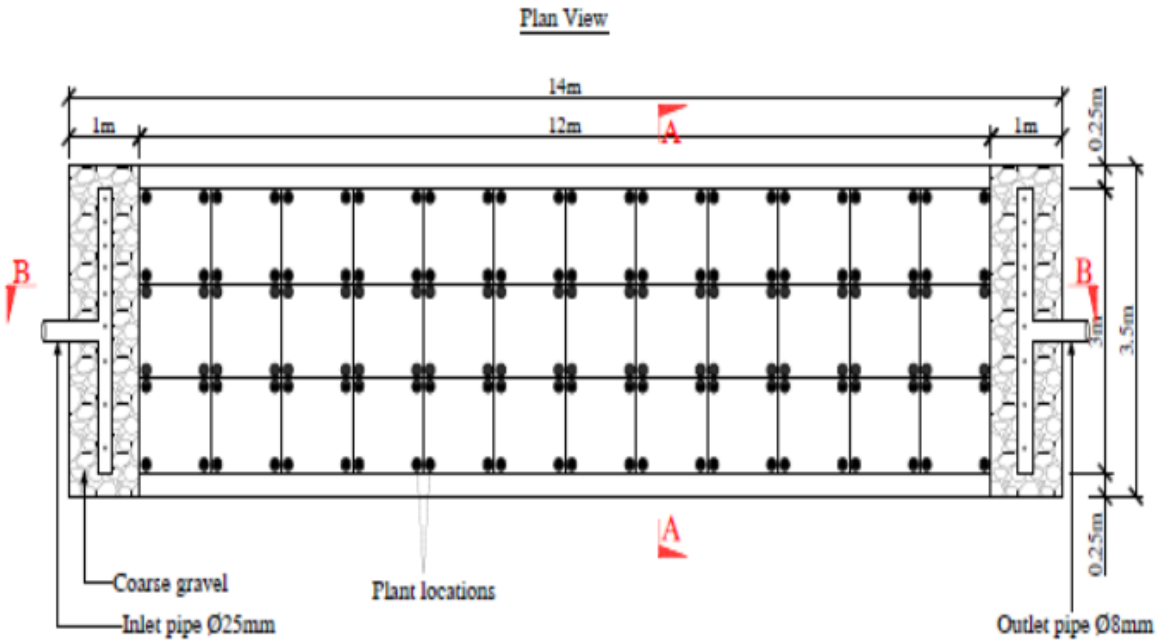


Fig. 3.1: Constructed wetland Plan

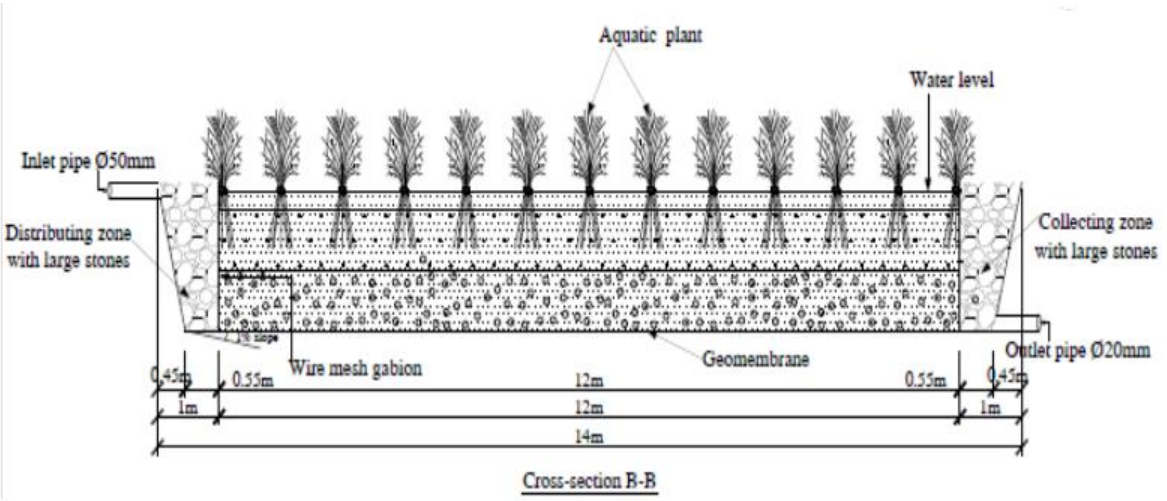


Fig. 3.1a: Constructed wetland cross-section

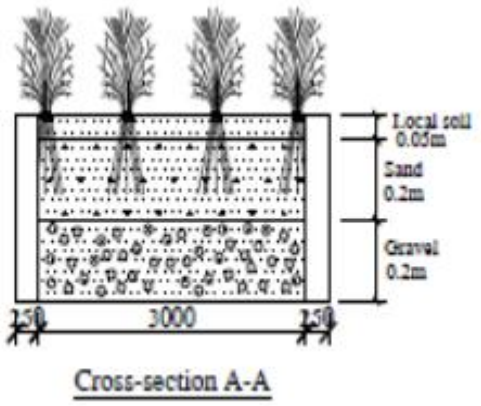
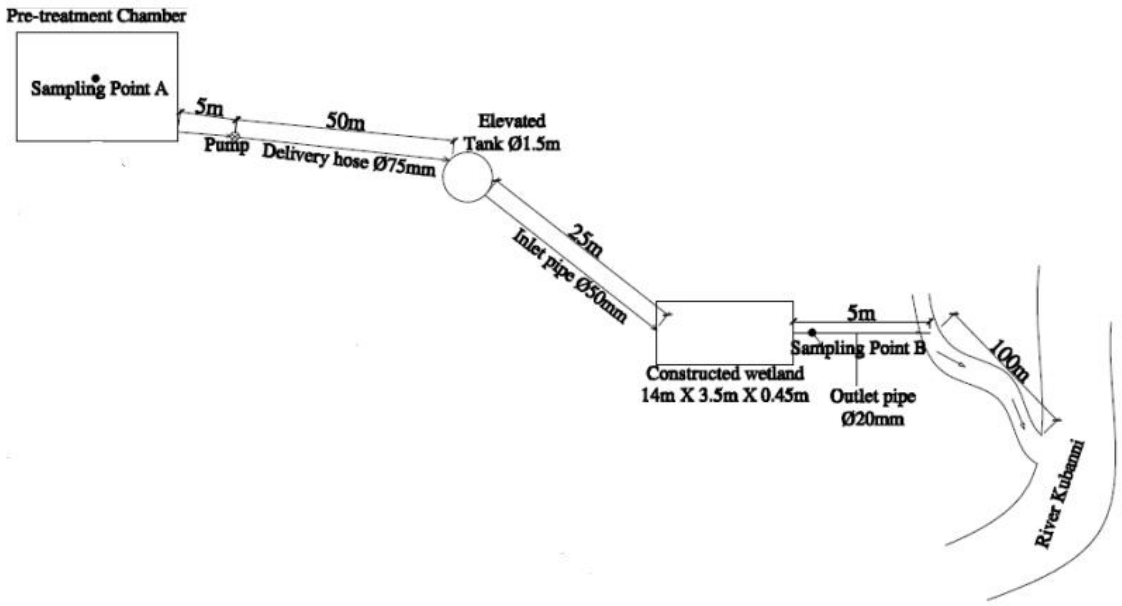


Fig. 3.1b: Constructed wetland cross-section

Coarse gravels of 50-100cm were placed at the inlet and outlet of the constructed wetland system, which help to avoid clogging and to facilitate relatively even water distribution throughout the cell and smooth collection of treated wastewater at the outlet. The constructed wetland cell was divided into three equal parts by planting clumps of three different macrophytes: Poaceae (Phragmites Karka)), Typhaceae (Typha australis) and Cannaceae (Canna indica) at approximately 4 plants/m^2. These plants were obtained from river banks around Zaria and its environs and identified by the Herbarium Unit of the Biological Science Department, ABU, Zaria. A soil moisture condition was maintained after planting the plants and the water level in the constructed wetland cell was slowly increased until the new shoots developed and grown. The excavation and construction of the wetland as well as planting the macrophytes took four weeks. The constructed wetland was irrigated with tap for four weeks before introducing a mixture of tap water and wastewater into the cell weekly for five weeks in a formulated percentage ratio of (80:20), (60:40), (40:60), (20:80) and (0:100) in order to reduce shock to the plants.

According to USEPA (1993) plants were allowed to become well established before the wastewater was introduced into the system; since the plants needed an opportunity to overcome the stress of transplanting before other stresses are introduced. This is because; the high oxygen demand of the waste water could inhibit initial plant growth. The wastewater from the sewer networks of Ahmadu Bello University was pumped using the pumping machine (Model: WP20X, Honda) of 5Hp/3600rpm capacity into an elevated storage tank of 3000 litres capacity and gradually released to the constructed wetland cell through pipe network (Fig.3.2).



Plan View

Fig. 3.2a: Diagrammatic sketch of experimental design

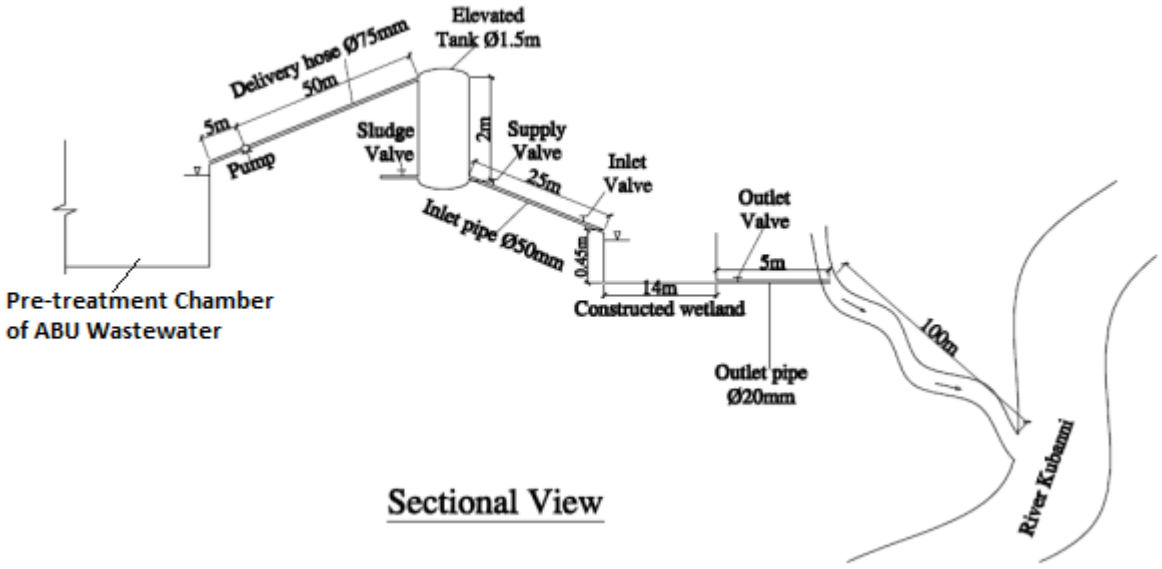
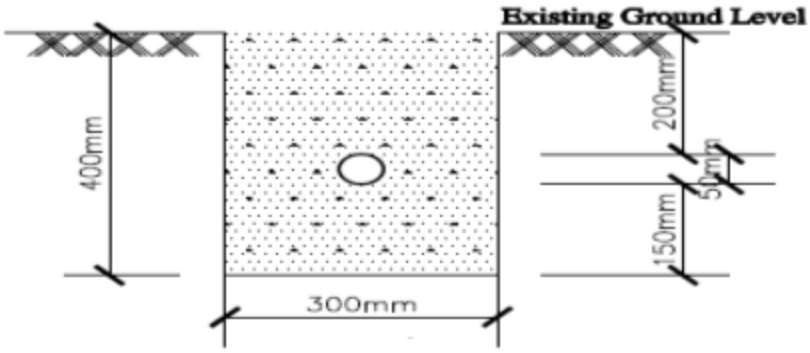
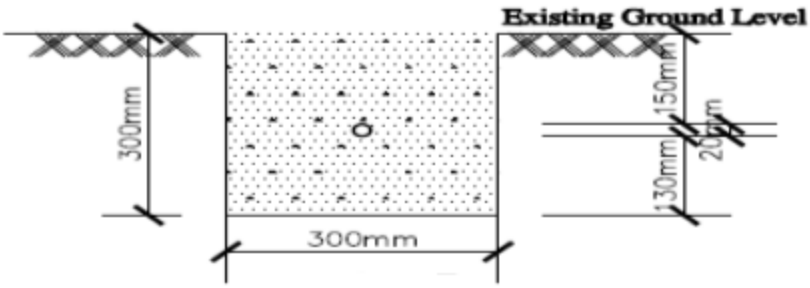


Fig. 3.2b: Diagrammatic sketch of experimental design





Section B-B

Fig. 3.2c: Cross sections of the pipe network

The storage tank also serves as a sedimentation and equalization tank to the constructed wetland. To reduce the substantial portion of the suspended solids from the raw wastewater entering the constructed wetland cell, a strainer was installed at the inlet suction hoist of the pump and a screen installed at the outlet of the storage tank leading to the pipe network supplying the wastewater to the constructed wetland cell. The wastewater from the storage tank into the wetland was controlled by a gate valve and distributed to the constructed wetland cell through a polyvinylchloride (PVC) pipe of size 25mm diameter, installed with flow control plastic gate-valves. The inflow and outflow rate was regulated using a stopwatch and measuring cylinder. The average inflow to constructed wetland was calculated by using the formula $(Q_i + Q_o)/2$, where Q_i and Q_o are inflow and outflow respectively (USEPA, 1993). The calculated wastewater hydraulic retention time was seven days, based on Darcy's law at 35.6% porosity. The experimental set up used in this study is shown in Plates I - XXIV.



Plate I: Excavation of the wetland



Plate II: Excavation of the wetland in progress



Plate III: Excavation of the drainage channel



Plate IV: Excavation of the drainage channel in progress



Plate V: Collection of soil samples using core cutter



Plate VI: Retrieval of core cutter



Plate VII: Heaps of sand and gravels for wetland construction



Plate VIII: Fetching of gravels for wetland construction



Plate IX: Gravel packing at inlet of the wetland



Plate X: Stones wrapped with gabion wire mesh at the inlet and outlet sections



Plate XI: Leveling of substratum



Plate XII: Piping work from elevated wastewater tank



Plate XIII: Piping work to wetland continued



Plate XIV: Piping at the inlet of the wetland



Plate XV: Piping at the outlet of the wetland



Plate XVI: Backfilling of trenches of pipe network

Excavation of pipeline and laying pipes with fittings were successfully completed and the following materials were used: storage tank of 3000 litres capacity, 25 metres length pipe of 50 mm diameter, 5 metres length pipe of 20 mm diameter, various fittings and water pump (Model: WP20X, Honda) of 5Hp/3600rpm capacity with suction and delivery holes. Two labourers and a plumber were involved in the execution of the plumbing work which took five (5 days) to complete and test-run.



Plate XVII: Sourcing of macrophytes



Plate XVIII: Planting of macrophytes (plants)

The macrophytes (plants) were sourced along the banks of River Kubanni. The younger plants were carefully selected and up-rooted with soils and bagged their roots with host soils in polythene bags to prevent loss of moisture and damage to them. Reasonable quantity of the plants was collected and transported with a pickup van to the project site and thereafter they were carefully planted. The sourcing and planting of macrophytes took one week, while the wetland was irrigated with tap water at the early growing stage of the plants for four weeks before introducing a mixture of tap water and wastewater into the cell weekly for five weeks in a formulated percentage ratio in order to reduce shock to the plants. It took the plants twelve (12) weeks to fully grow and the wetland system to establish biofilm.



Plate XIX: Tap water initially used to irrigate the constructed wetland



Plate XX: Early stage of the constructed wetland



Plate XXI: Pumping wastewater from waste stabilization pond to the elevated tank



Plate XXII: Weeding and maintenance of the constructed wetland



Plate XXIII: Routine Maintenance activities of the constructed wetland



Plate XXIV (a): Cross section of fully grown constructed wetland



Plate XXIV (b): Cross section of fully grown constructed wetland



Plate XXIV (c): Cross section of fully grown constructed wetland

3.2.6 Sample Collection and Analysis

Samples collection started three months after construction and stabilization of the wetland allowing sufficient time for the establishment of vegetation and biofilm. The analysis carried out in this study is shown in Plates XXV – XXVIII.

Samples were taken every 7 days (hydraulic retention time). One litre of wastewater sample from influent and one litre wastewater sample from effluent of the constructed wetland and that of waste stabilization pond system of ABU were collected using clean dried plastic bottles. The sample bottles were carefully and legibly labelled and sent to Water Resources and Environmental Engineering Department Laboratory of ABU for analysis.

The sampling protocols were in line with the APHA standards (2012). Wastewater characterization was carried out for the following physico-chemical water quality parameters; Samples were measured for pH, Temperature (T), Total Suspended solids (TSS), Biological Oxygen Demand (BOD^5), Chemical Oxygen Demand (COD), Phosphate (PO_4^-), Ammonia Nitrogen (NH_4^+), Nitrate (NO_3^-), Total Coliforms in accordance with the standard procedure of APHA (2012), while heavy metals: Lead (Pb), Iron (Fe), Zinc (Zn), Cadmium (Cd), Magnesium (Mg), Chromium (Cr), Manganese (Mn), Silver (Ag), Copper (Cu), and Cobalt (Co), were measured using Atomic Absorption Spectrophotometer (Model AA-670). The pH and temperature of the influent and effluent of the system were measured insitu using a pH meter and thermometer respectively.

All wastewater samples for heavy metal analyses were digested with mixed Nitric Acid (5 ml conc. HNO_3) in a hot plate for 45 minutes, and allowed to cool, filtered and then analysed using flame Atomic Absorption Spectrophotometer (Model AA-670). The

digestion was done in order to destroy any organic matter present in the samples prior to analysis by Atomic Absorption Spectrophotometer.



Plate XXV: Wastewater sample



Plate XXVI: Samples prepared for COD test analysis



Plate XXVII: BOD determination

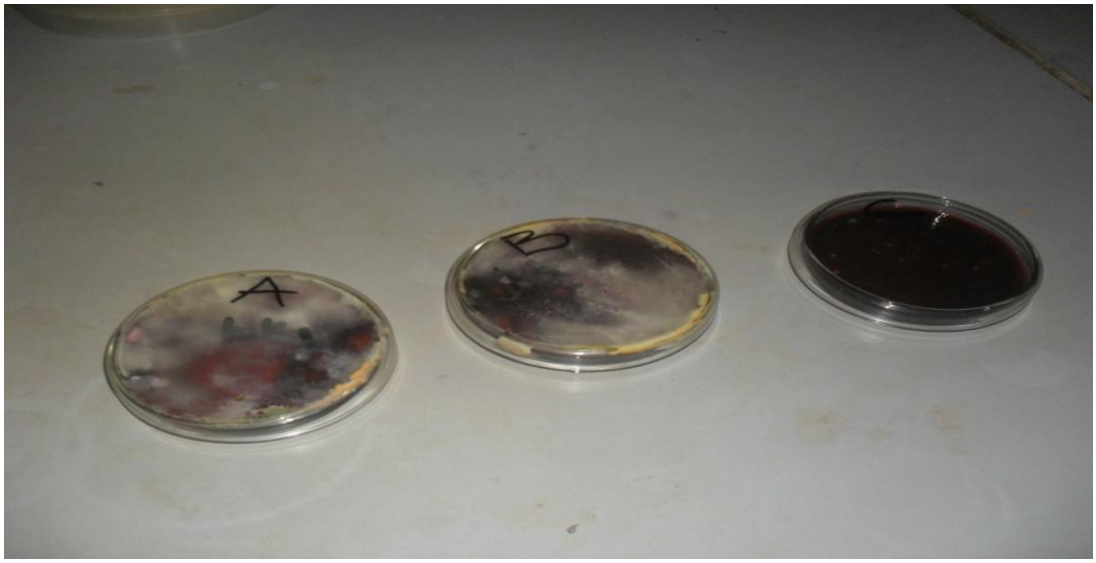


Plate XXVIII: Total Coliform determination

3.2.7 Modeling of Horizontal Subsurface Flow Constructed Wetland for Removal of Heavy Metals from ABU Wastewater

With the increasing number of constructed wetlands being built, the modeling of wetland function and performance becomes increasingly important. Much of the literature on models for constructed wetlands (mostly HF CWs) refers to simple first-order decay models (e.g., Pastor *et al*, 2003; Stein *et al*, 2006; Tomenko *et al*, 2007) where only effluent concentrations are predicted based on influent concentrations. However, the authors claimed that this suitability is only true when model parameters from systems operating under similar conditions (i.e., climatic conditions, wastewater composition, porous filter material, and plant species) are available. The main objective of this modeling study is to better understand the treatment processes in constructed wetlands and to improve the design, management, monitoring and maintenance of constructed wetlands.

3.2.8 Determination of Treatment Efficiency of Constructed Wetland

The removal efficiency of the constructed wetland with respect to the for selected parameters was calculated using the formulae proposed by Garg *et al*. (2008); *Saad et al*. (2010) and Lo *et al*. (2012) who stated that:

Percent removal efficiency, $\%R = \frac{C_i - C_e}{C_i} \times 100$

Where C_i= Influent concentration, mg/l;

C_e= Effluent concentration, mg/l

3.2.9 Design Model

A two- parameter model commonly known as the first- order dynamic model proposed by Kadlec and Knight (1996) was used to predict only effluent concentrations based on influent concentrations. The wastewater samples were collected at influent and effluent of the constructed wetland at 7days retention time for 10 weeks period to evaluate the efficiencies of removal pollutants, while steady and plug flow conditions were observed. The analyses were done according to standard methods (APHA 1998). The first-order model equation can be written as eqn. (3.1 or 3.2).

$$\frac{dC}{dt} = -\frac{kv}{q} C \qquad (3.1)$$

$$\frac{dC}{dx} = -\frac{k}{q} C \qquad (3.2)$$

Where C = the concentration of the quantity concerned (mg/L),

t = the hydraulic resident time (h),

k_v = volumetric rate constant (h^{-1}),

x = the fraction of the distance through the wetland,

k = the areal rate constant (m/h), and

q = the hydraulic loading rate (m/h)

$$\frac{dC}{dt} = -kv(C - C*) \qquad (3.3)$$

Where C* = the background concentration

The key to the quantitative model of wetland operation is the determination of the volumetric rate constant, k_v. Solution of the equation gives a linear relationship in the concentration logarithm with the residence time. The expression for the concentration logarithm at any residence time can be written as eqn. (3.4).

$$\ln \frac{Co - C*}{Ci - C*} = -k_v t \quad (3.4)$$

Where C_o = the outlet concentration, (mg/l),

C_i = the inlet concentration, (mg/l).

C*= the background concentration (2.155mg/L).

3.2.10 Statistical Analysis

Statistical analyses of the collected data were carried out by means of using a sub-program of Microsoft Office Software EXCEL XP and SPSS program. The sub-program of Microsoft Office Software EXCEL XP was used to determine the linear relationship in the concentration logarithm with the residence time, while the SPSS program was used to establish the relationship between heavy metal removal and resident time, the goodness of fit, and the coefficients of dependent Variable (concentration logarithm). Also, statistical analyses of removal efficiency of the heavy metals by the waste stabilization pond and constructed wetland system were assessed and their levels of significance determined using SPSS program.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 General Treatment Performance

The results of laboratory analysis of influent and effluent wastewater samples from ABU waste stabilization pond and constructed wetland obtained weekly for 10 weeks (i.e. from July to September) are discussed in this chapter.

4.2. Removal Efficiencies for Lead (Pb)

The results of the removal of Lead by waste stabilization pond and constructed wetland for ten (10) weeks are showed in Table 4.1. The inlet concentrations, outlet concentrations of the lead (Pb) in waste stabilization pond and constructed wetland is presented graphically in Figure 4.1, while the removal efficiency of lead from waste stabilization pond and constructed wetland is shown in Figure 4.2.

Table 4.1: Inlet Concentrations, Outlet Concentrations and Removal Efficiencies of the Lead (Pb) from Waste Stabilization Pond and Constructed Wetland

Hydraulic resident time (Weeks)	Inlet Concentration (mg/L)	Outlet Concentration (mg/L)		Removal efficiency (%)	
		WSP	CWS	WSP	CWS
1	0.824	0.740	0.279	10.21	66.14
2	0.873	0.781	0.332	10.53	61.97
3	0.798	0.720	0.245	9.81	69.3
4	0.912	0.821	0.359	10.00	60.64
5	0.881	0.823	0.310	6.56	64.81
6	0.834	0.762	0.215	8.62	74.22
7	0.765	0.694	0.101	9.25	86.8
8	0.765	0.686	0.101	10.31	86.8
9	0.770	0.675	0.108	10.4	85.97
10	0.789	0.709	0.114	10.2	85.56

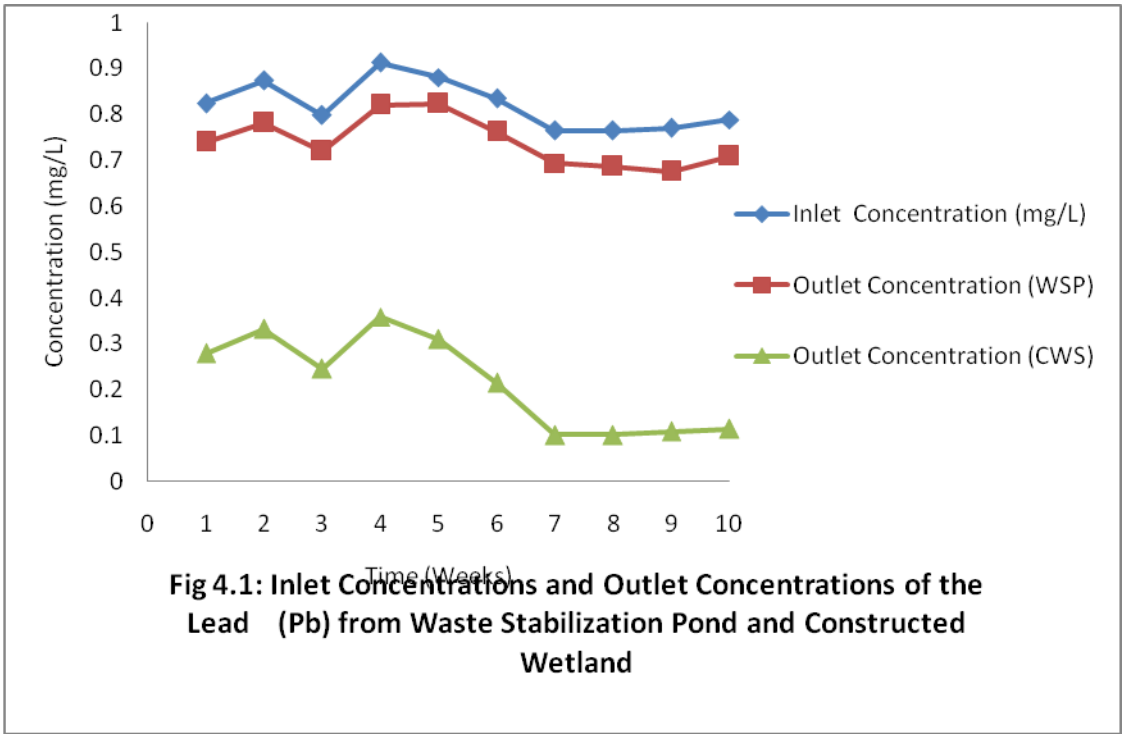


Fig 4.1: Inlet Concentrations and Outlet Concentrations of the Lead (Pb) from Waste Stabilization Pond and Constructed Wetland

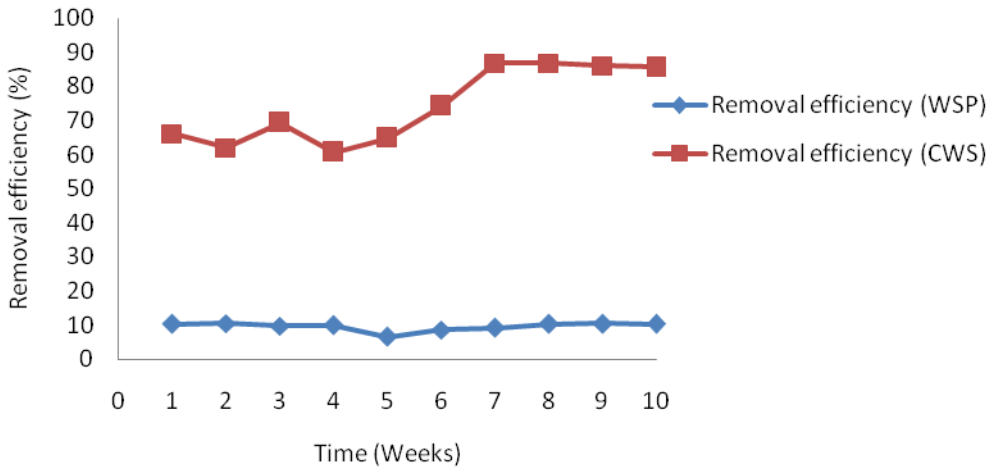


Fig 4.2:Removal Efficiencies of the Lead (Pb) from Waste Stabilization Pond and Constructed Wetland

The removal efficiency of Lead (Pb) by waste stabilization pond and constructed wetland ranged from 6.56 - 10.53% and 61.97- 86.8% respectively during the 7 days retention time and for the entire ten (10) weeks of the study. The result clearly shows that the removal efficiency of Lead by constructed wetland was much higher than that by waste stabilization pond. Similar to this, is the result of Masi *et al*. (2013) who reported that the removal of Lead by a constructed wetland was 92%. It is assumed that Lead removal from wetland by macrophytes depended on the biomass of the roots.

4.3. Removal Efficiency for Zinc (Zn)

The results of the removal of Zinc (Zn) by waste stabilization pond and constructed wetland are showed in Table 4.2. The inlet concentrations, outlet concentrations of the Zinc (Zn) in waste stabilization pond and constructed wetland is presented graphically in Figure 4.3, while the removal efficiency of Zinc from waste stabilization pond and constructed wetland is shown in Figure 4.4.

Table 4.2: Inlet Concentrations, Outlet Concentrations and Removal Efficiencies of the Zinc (Zn) from Waste Stabilization Pond and Constructed Wetland

Hydraulic resident time (Weeks)	Inlet Concentration (mg/L)	Outlet Concentration (mg/L)		Removal efficiency (%)	
		WSP	CWS	WSP	CWS
1	0.812	0.761	0.499	6.29	38.6
2	0.983	0.932	0.647	5.15	34.18
3	0.926	0.860	0.533	7.1	42.44
4	0.810	0.752	0.442	7.12	45.43
5	0.842	0.784	0.424	6.93	49.64
6	0.842	0.814	0.424	6.98	49.64
7	0.731	0.677	0.270	7.41	63.06
8	0.711	0.657	0.202	7.62	71.59
9	0.825	0.767	0.262	6.99	68.24
10	0.870	0.804	0.245	7.64	71.83

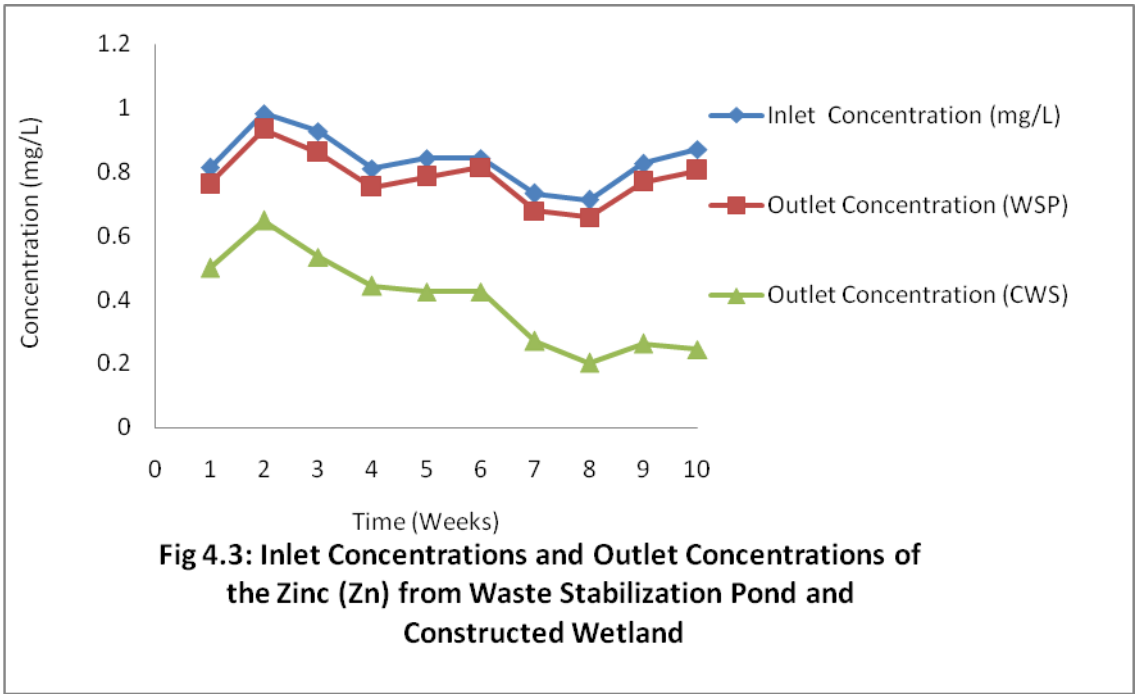


Fig 4.3: Inlet Concentrations and Outlet Concentrations of the Zinc (Zn) from Waste Stabilization Pond and Constructed Wetland

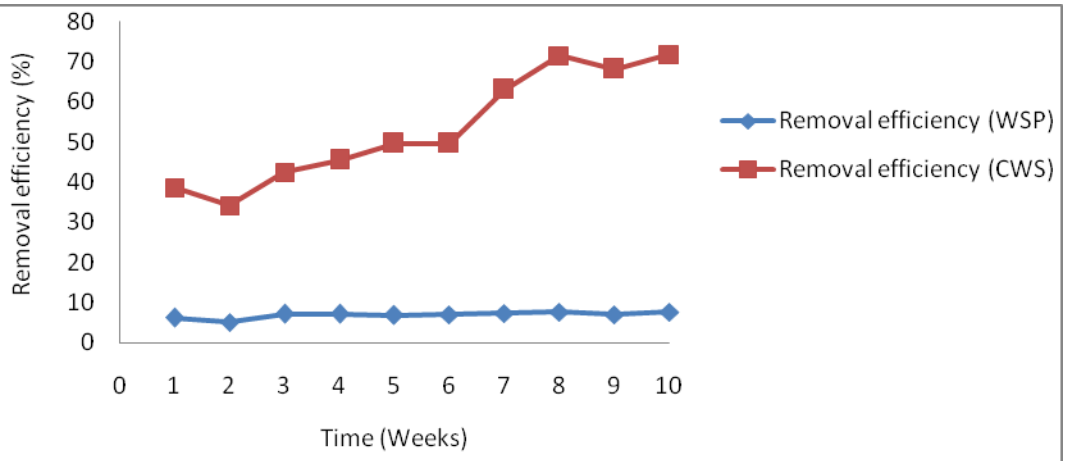


Fig 4.4:Removal Efficiencies of the Zinc (Zn) from Waste Stabilization Pond and Constructed Wetland

After ten weeks of treatment, the removal of Zinc (Zn) by waste stabilization pond and the constructed wetland ranged from 5.15 – 7.64% and 34.18 – 71.83% respectively. The average removal of Zinc by waste stabilization pond for the period of ten weeks was 6.92%, while that of constructed wetland was 53.47%. The result shows that constructed wetland was more effective in removal of Zinc from the ABU wastewater. Similarly, the studies of Masi *et al.,* (2013), Madera-Parra *et al.* (2013) and Rai *et al*., (2015) revealed that the maximum removal of Zinc in constructed wetlands are 55%, 62% and 68.4% respectively.

4.4. Removal Efficiency for Manganese (Mn)

The results of the removal of Manganese by waste stabilization pond and constructed wetland are shown in Table 4.3. The inlet concentrations, outlet concentrations of the Manganese (Mn) in waste stabilization pond and constructed wetland is presented

graphically in Figure 4.5, while the removal efficiency of Manganese from waste stabilization pond and constructed wetland is shown in Figure 4.6.

Table 4.3: Inlet Concentrations, Outlet Concentrations and Removal Efficiencies of the Manganese (Mn) from Waste Stabilization Pond and Constructed Wetland

Hydraulic resident time (Weeks)	Inlet Concentration (mg/L)	Outlet Concentration (mg/L)		Removal efficiency (%)		Parameters for Irrigation	
		WSP	CWS			FAO (1985) (mg/L)	WHO (1994) (mg/L)
1	0.789	0.743	0.396	5.82	49.81	0.2	0.5-1.50
2	0.836	0.783	0.398	6.34	52.39		
3	0.825	0.773	0.295	6.29	64.24		
4	0.824	0.768	0.276	6.78	66.50		
5	0.912	0.858	0.290	5.92	68.20		
6	0.916	0.856	0.324	6.56	64.63		
7	0.888	0.829	0.262	6.70	70.50		
8	0.873	0.821	0.174	5.96	80.10		
9	0.762	0.710	0.001	6.84	80.07		
10	0.779	0.725	0.018	6.91	97.69		

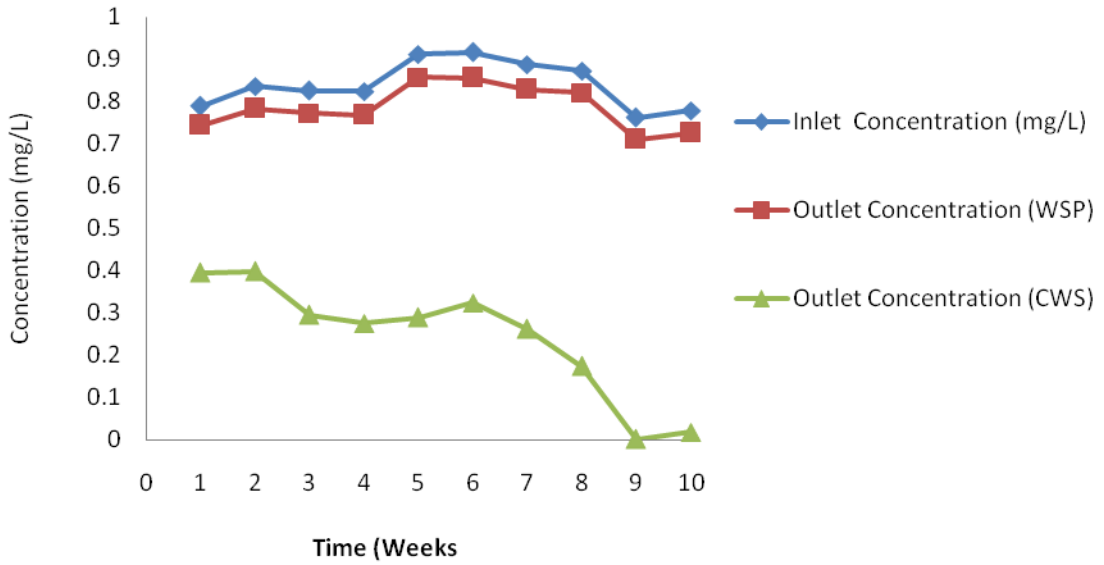


Fig 4.5: Inlet Concentrations and Outlet Concentrations of the Manganese (Mn) from Waste Stabilization Pond and Constructed Wetland

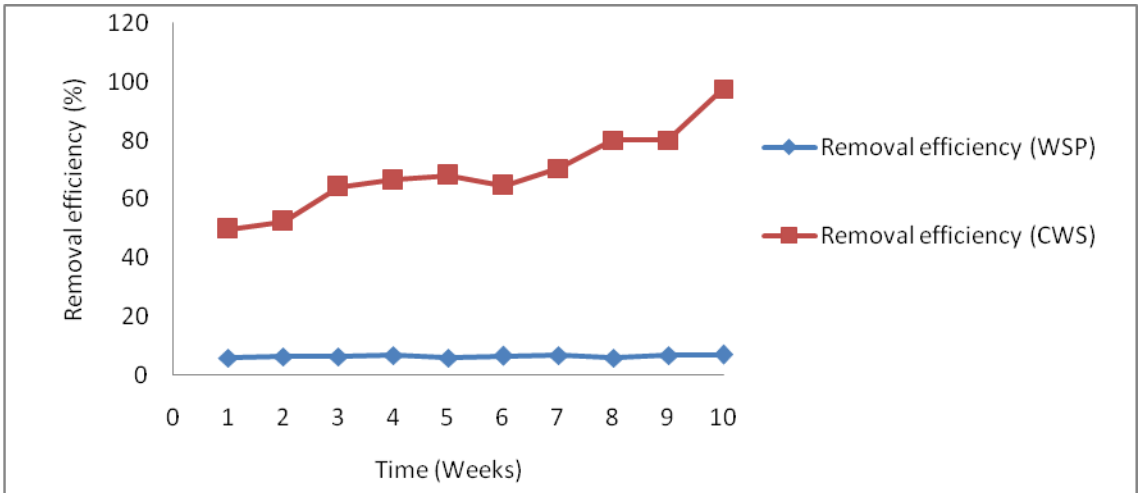


Fig 4.6:Removal Efficiencies of the Manganese (Mn) from Waste Stabilization Pond and Constructed Wetland

The removal of Manganese (Mn) by waste stabilization pond ranged 5.82 – 6.91% while that by the constructed wetland ranged from 49.81- 97.69% during the period of ten weeks treatment. The average removal of Manganese by constructed wetland was 69.41% while that by waste stabilization pond was 6. 41%. The removal efficiency of Mn by constructed wetland was more effective. Similarly, the studies carried out by Masi *et al*., (2013) and Rai *et al.*, (2013) revealed that the maximum removal of Mn by constructed wetland were 87% and 62.22% respectively.

4.5. Removal Efficiency for Magnesium (Mg)

The results of the removal of Magnesium by waste stabilization pond and constructed wetland are showed in Table 4.4. The inlet concentrations, outlet concentrations of the Magnesium (Mg) in waste stabilization pond and constructed wetland is presented graphically in Figure 4.7, while the removal efficiency of Magnesium from waste stabilization pond and constructed wetland is shown in Figure 4.8.

Table 4.4: Inlet Concentrations, Outlet Concentrations and Removal Efficiencies of the Magnesium (Mg) from Waste Stabilization Pond and Constructed Wetland

Hydraulic resident time (Weeks)	Inlet Concentration (mg/L)	Outlet Concentration (mg/L)		Removal efficiency (%)		Parameters for Irrigation	
						FAO (1985) (mg/L)	WHO (1994) (mg/L)
		WSP	CWS	WSP	CWS		
1	4.125	3.877	1.915	6.02	53.58	20-120	30-150
2	4.061	3.814	1.918	6.09	52.77		
3	3.90	3.627	1.681	7.0	56.9		
4	4.02	3.743	1.56	6.89	61.19		
5	3.675	3.421	1.283	6.92	65.08		
6	3.585	3.333	1.182	7.04	67.03		
7	3.84	3.53	0.998	8.07	74.01		
8	4.02	3.719	1.085	7.48	73.01		
9	3.942	3.64	0.808	7.67	79.5		
10	3.88	3.601	0.776	7.18	80		

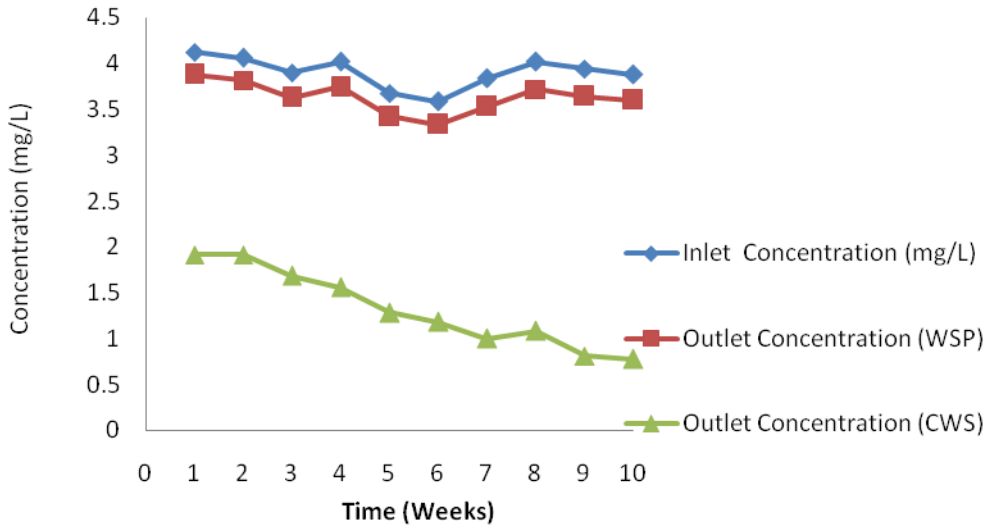


Fig 4.7: Inlet Concentrations and Outlet Concentrations of the Magnesium (Mg) from Waste Stabilization Pond and Constructed Wetland

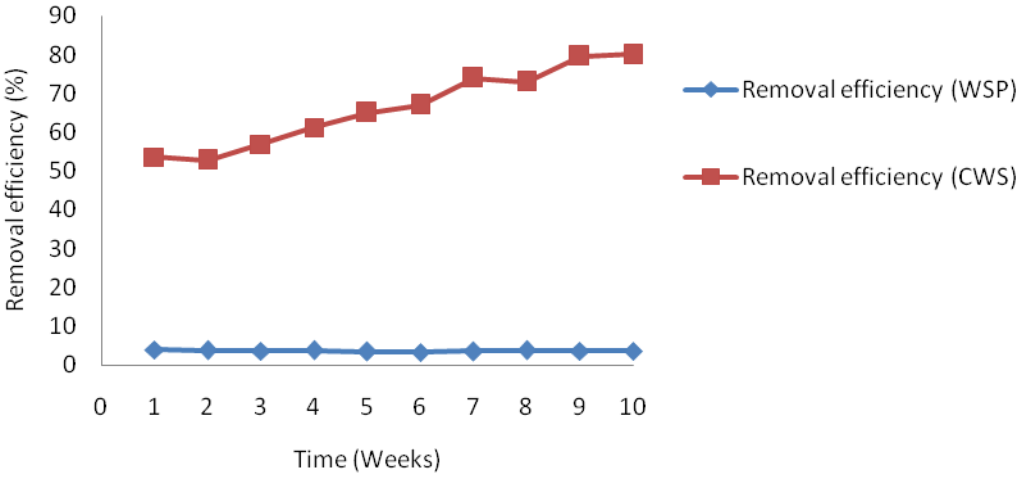


Fig 4.8: Removal Efficiencies of the Magnesium (Mg) from Waste Stabilization Pond and Constructed Wetland

The removal of Magnesium (Mg) by the constructed wetland and waste stabilization pond ranged from 52.77- 80% and 6.02 – 7.67% respectively after (10) weeks of the study. The result shows that the Mg removal efficiency by constructed wetland was more effective than that by waste stabilization pond. The macrophytes might have provided biomass of the roots for attachment of microorganisms that took up the pollutant (Zhang *et al*., 2009).

4.6. Removal Efficiency for Silver (Ag)

The results of the removal of Silver by waste stabilization pond and constructed wetland are showed in Table 4.5. The inlet concentrations, outlet concentrations of the Silver (Ag) in waste stabilization pond and constructed wetland is presented graphically in Figure 4.9, while the removal efficiency of Silver from waste stabilization pond and constructed wetland is shown in Figure 4.10.

Table 4.5: Inlet Concentrations, Outlet Concentrations and Removal Efficiencies of the Silver (Ag) from Waste Stabilization Pond and Constructed Wetland

Hydraulic resident time (Weeks)	Inlet Concentration (mg/L)	Outlet Concentration (mg/L)		Removal efficiency (%)	
		WSP	CWS	WSP	CWS
1	0.208	0.194	0.119	6.85	42.79
2	0.226	0.21	0.121	7.02	46.46
3	0.21	0.195	0.102	6.92	51.43
4	0.175	0.163	0.074	6.81	57.71
5	0.169	0.155	0.064	8.05	62.13
6	0.21	0.195	0.088	6.96	58.10
7	0.202	0.187	0.08	7.38	60.40
8	0.218	0.202	0.09	7.44	63.30
9	0.192	0.177	0.067	7.62	65.10
10	0.202	0.186	0.063	8.00	68.81

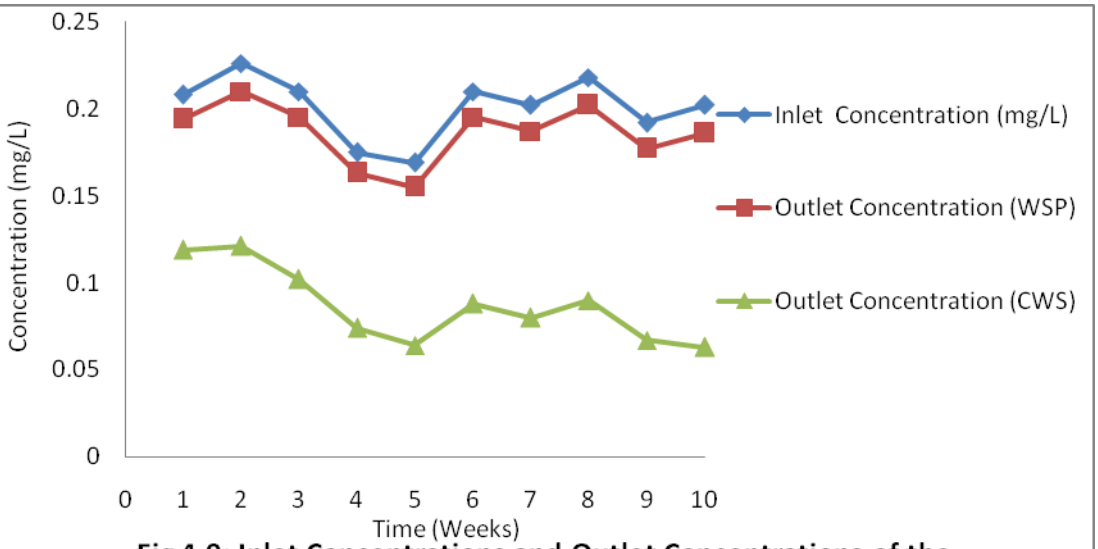


Fig 4.9: Inlet Concentrations and Outlet Concentrations of the Silver (Ag) from Waste Stabilization Pond and Constructed Wetland

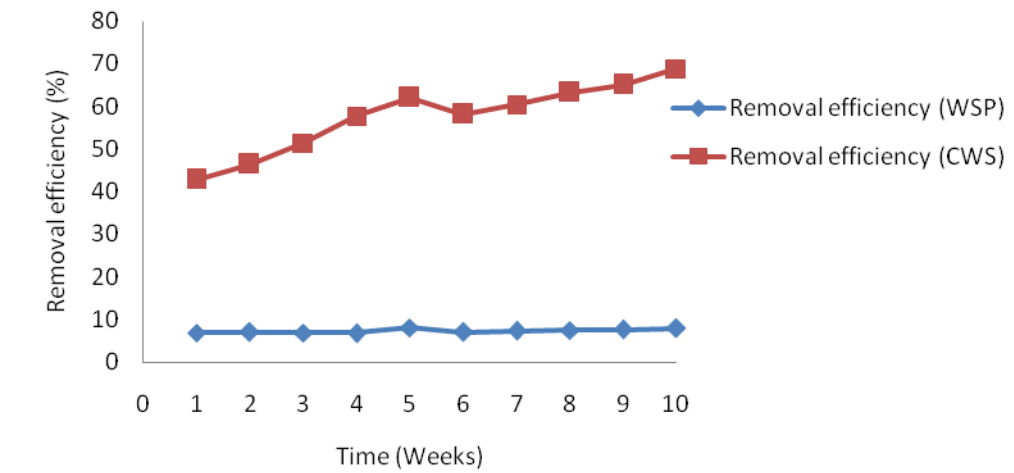


Fig 4.10: Removal Efficiencies of the Silver (Ag) from Waste Stabilization Pond and Constructed Wetland

The removal of Silver (Ag) by the constructed wetland and waste stabilization pond ranged from 46.46 – 68.81 % and 6.81 – 8.05% respectively after 7 days retention time for the

period of ten (10) weeks of the study. The constructed wetland performed much better in the removal of Ag. A study done on constructed wetland by Dipu, (2013) revealed that the occurrence of both fibrous and tap root system of aquatic plants enables them to absorb heavy metals from both soil and aqueous medium.

4.7. Removal Efficiency for Cobalt (Co)

The results of the removal of Cobalt by waste stabilization pond and constructed wetland are showed in Table 4.6. The inlet concentrations, outlet concentrations of the Cobalt (Co) in waste stabilization pond and constructed wetland is presented graphically in Figure 4.11, while the removal efficiency of Cobalt from waste stabilization pond and constructed wetland is shown in Figure 4.12.

Table 4.6: Inlet Concentrations, Outlet Concentrations and Removal Efficiencies of the Cobalt (Co) from Waste Stabilization Pond and Constructed Wetland

Hydraulic resident time (Weeks)	Inlet Concentration (mg/L)	Outlet Concentration (mg/L)		Removal efficiency (%)	
		WSP	CWS	WSP	CWS
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0.015	0.014	0.011	5.2	26.67
5	0.015	0.014	0.01	5.8	33.33
6	0.015	0.015	0.01	5.12	33.33
7	0.021	0.02	0.013	4.21	38.10
8	0.019	0.018	0.011	4.68	42.11
9	0.012	0.011	0.004	4.98	66.67
10	0.01	0.009	0.001	5.14	90

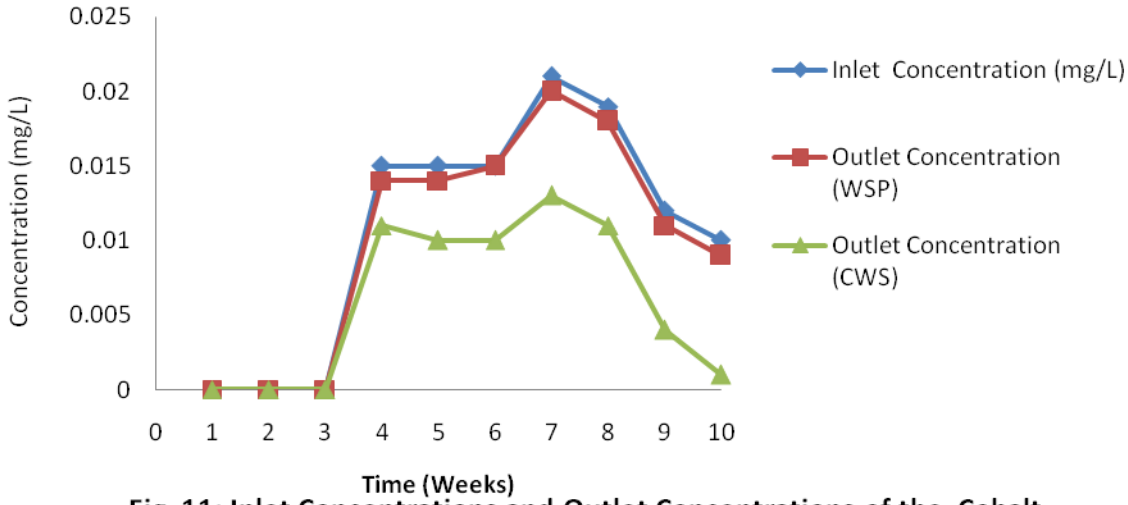


Fig. 11: Inlet Concentrations and Outlet Concentrations of the Cobalt (Co) from Waste Stabilization Pond and Constructed Wetland

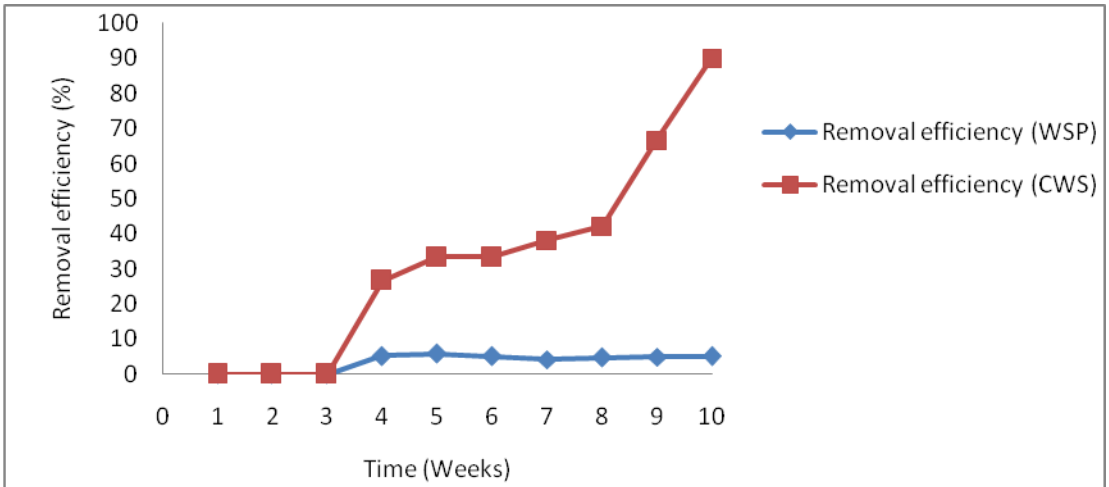


Fig 4.12: Removal Efficiencies of the Cobalt (Co) from Waste Stabilization Pond and Constructed Wetland

The removal of Cobalt (Co) by the constructed wetland and waste stabilization pond ranged from 0 – 90 % and 0 - 5.8 % respectively after 7 days retention time for the period of ten (10) weeks of the study. Similarly, the study by Masi *et al*., (2013) revealed that the maximum removal of Co by constructed wetland was 49%. It was observed that there were no traces of cobalt in the wastewater in weeks 1, 2 and 3.

4.8. Removal Efficiency for Chromium (Cr)

The results of the removal of Chromium by waste stabilization pond and constructed wetland are showed in Table 4.7. The inlet concentrations, outlet concentrations of the Chromium (Cr) in waste stabilization pond and constructed wetland is presented graphically in Figure 4.13, while the removal efficiency of Chromium from waste stabilization pond and constructed wetland is shown in Figure 4.14.

Table 4.7: Inlet Concentrations, Outlet Concentrations and Removal Efficiencies of the Chromium (Cr) from Waste Stabilization Pond and Constructed Wetland

Hydraulic resident time (Weeks)	Inlet Concentration (mg/L)	Outlet Concentration (mg/L)		Removal efficiency (%)	
		WSP	CWS	WSP	CWS
1	0.91	0.878	0.439	3.48	51.76
2	0.902	0.868	0.420	3.81	53.44
3	0.886	0.850	0.393	4.02	55.64
4	0.889	0.853	0.369	4.00	58.49
5	0.862	0.828	0.300	3.98	65.19
6	0.908	0.873	0.301	3.86	66.85
7	0.798	0.765	0.246	4.08	69.17
8	0.884	0.848	0.225	4.12	74.55
9	0.885	0.849	0.164	4.09	81.47
10	0.897	0.860	0.121	4.11	86.51

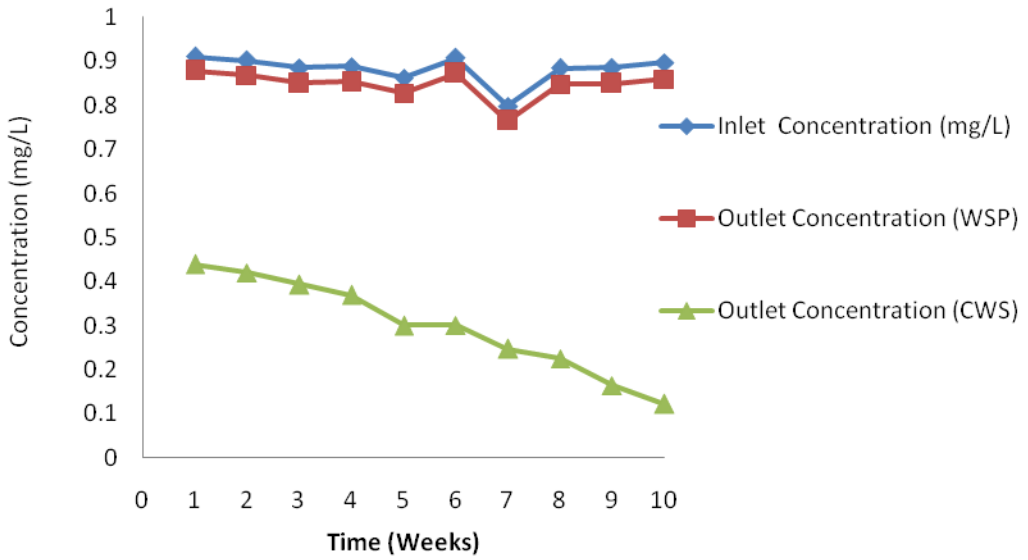


Fig 4.13 : Inlet Concentrations and Outlet Concentrations of the Chromium (Cr) from Waste Stabilization Pond and Constructed Wetland

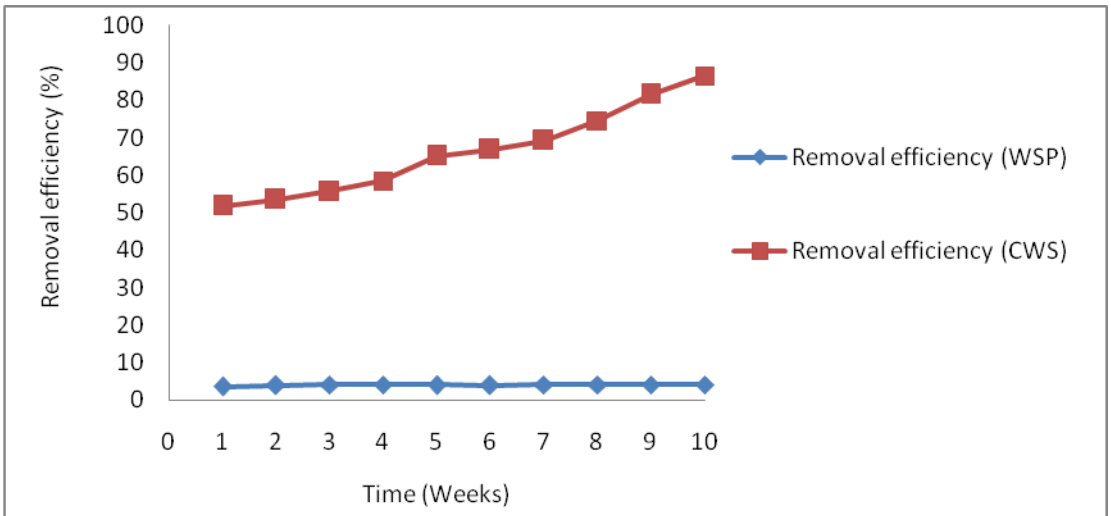


Fig 4.14: Removal Efficiencies of the Chromium (Cr) from Waste Stabilization Pond and Constructed Wetland

The removal of Chromium (Cr) by the constructed wetland and waste stabilization pond ranged from 51.76 – 86.51 % and 3.48 - 4.12% respectively after 7 days retention time for the period of ten (10) weeks of the study. Similarly, the studies carried out by Masi *et al.* (2013) and Rai *et al*., (2013) revealed that removals of Cr by constructed wetland are 35% and 81.63% respectively.

4.9. Removal Efficiency for Cadmium (Cd)

The results of the removal of Cadmium by waste stabilization pond and constructed wetland are showed in Table 4.8. The inlet concentrations, outlet concentrations of the Cadmium (Cd) in waste stabilization pond and constructed wetland is presented graphically in Figure 4.15, while the removal efficiency of Cadmium from waste stabilization pond and constructed wetland is shown in Figure 4.16.

Table 4.8: Inlet Concentrations, Outlet Concentrations and Removal Efficiencies of the Cadmium (Cd) from Waste Stabilization Pond and Constructed Wetland

Hydraulic resident time (Weeks)	Inlet Concentration (mg/L)	Outlet Concentration (mg/L)		Removal efficiency (%)	
		WSP	CWS	WSP	CWS
1	0.125	0.12	0.068	3.71	45.6
2	0.105	0.101	0.054	3.84	48.57
3	0.121	0.117	0.059	3.68	51.24
4	0.107	0.102	0.047	4.32	56.07
5	0.105	0.1	0.043	4.41	59.04
6	0.124	0.118	0.05	4.6	59.68
7	0.119	0.114	0.042	4.61	64.71
8	0.120	0.115	0.037	4.53	69.17
9	0.114	0.109	0.029	4.16	74.56
10	0.122	0.117	0.013	4.44	89.34

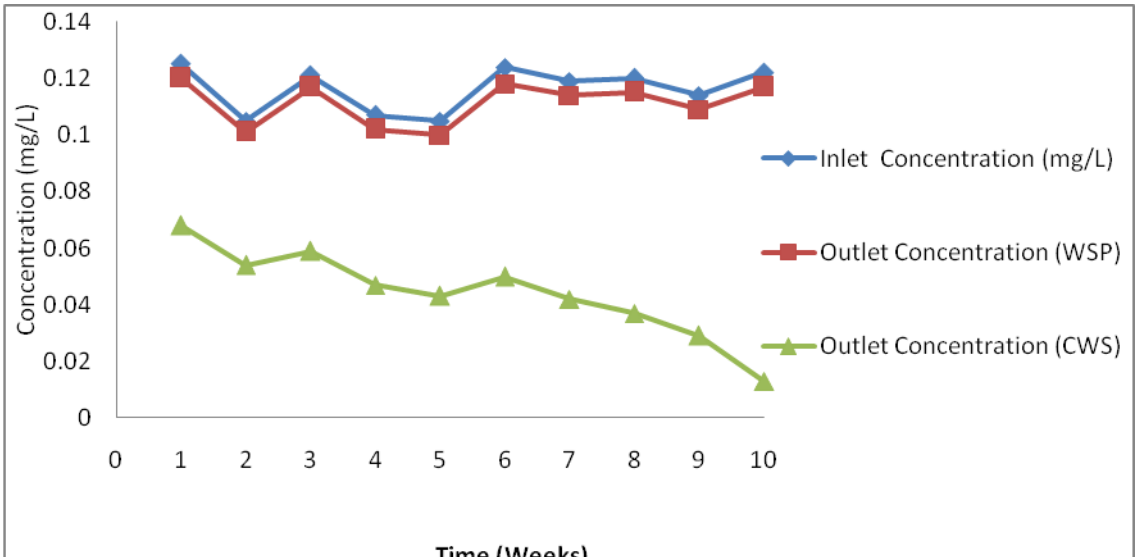


Fig 4.15: Inlet Concentrations and Outlet Concentrations of the Cadmium (Cd) from Waste Stabilization Pond and Constructed Wetland

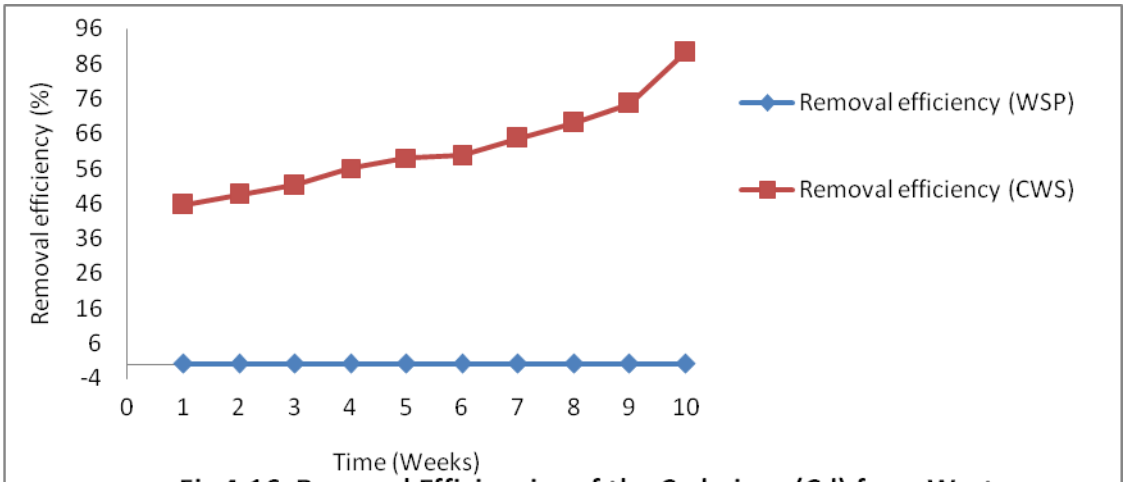


Fig 4.16: Removal Efficiencies of the Cadmium (Cd) from Waste Stabilization Pond and Constructed Wetland

The removal of Cadmium (Cd) by the constructed wetland and waste stabilization pond ranged from 45.6 – 89.34 % and 3.71 – 4.61% respectively after 7 days retention time for the period of ten (10) weeks of the study. Similarly, the study done by Home *et al*., (2010) using different mixes of macrophytes at 8days retention time revealed that the maximum removal of Cd in constructed wetland is 80.7%.

4.10. Removal Efficiency for Iron (Fe)

The results of removal of Iron by waste stabilization pond and constructed wetland are showed in Table 4.9. The inlet concentrations, outlet concentrations of the Iron (Fe) in waste stabilization pond and constructed wetland is presented graphically in Figure 4.17, while the removal efficiency of Iron from waste stabilization pond and constructed wetland is shown in Figure 4.18.

Table 4.9: Inlet Concentrations, Outlet Concentrations and Removal Efficiencies of the Iron (Fe) from Waste Stabilization Pond and Constructed Wetland

Hydraulic resident time (Weeks)	Inlet Concentration (mg/L)	Outlet Concentration (mg/L)		Removal efficiency (%)		Parameters for Irrigation	
						FAO (1985) (mg/L)	WHO (1994) (mg/L)
		WSP	CWS				
1	10.15	9.074	5.875	10.6	42.12	0.20-1.50	0.20-1.50
2	10.02	9.93	5.61	9.41	44.01		
3	10.8	9.587	5.832	11.23	46		
4	11	9.834	5.608	10.6	49.02		
5	10.42	9.252	5.002	11.21	52		
6	10.4	9.429	4.769	9.34	54.14		
7	10.61	9.028	4.456	10.1	58		
8	10.48	9.541	3.981	8.96	62.01		
9	10.42	9.399	3.562	9.8	65.08		
10	10	8.899	3.182	11.01	68.18		

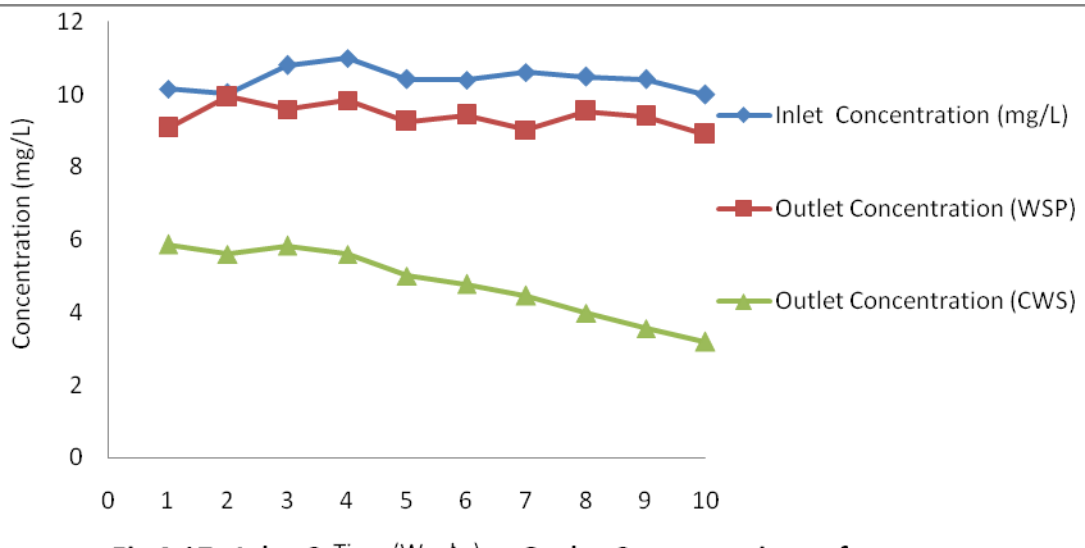


Fig 4.17: Inlet Concentrations, Outlet Concentrations of the Iron (Fe) from Waste Stabilization Pond and Constructed Wetland

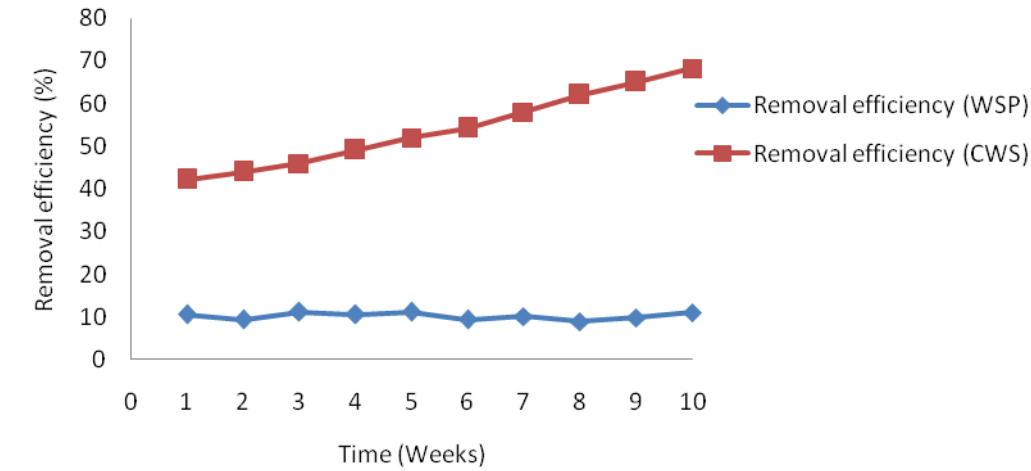


Fig 4.18: Removal Efficiencies of the Iron (Fe) from Waste Stabilization Pond and Constructed Wetland

The removal of Iron (Fe) by the constructed wetland and waste stabilization pond ranged from 42.12 – 68.18% and 8.96 - 11.23% respectively after 7 days retention time for the

period of ten (10) weeks of the study. The constructed wetland system proved to be more efficient (42.12 – 68.18%) in removal of Fe than the waste stabilization pond.

4.11. Removal Efficiency for Copper (Cu)

The results of removal of Copper by waste stabilization pond and constructed wetland are showed in Table 4.10. The inlet concentrations, outlet concentrations of the Copper (Cu) in waste stabilization pond and constructed wetland is presented graphically in Figure 4.19, while the removal efficiency of Copper from waste stabilization pond and constructed wetland is shown in Figure 4.20.

Table 4.10: Inlet Concentrations, Outlet Concentrations and Removal Efficiencies of the Copper (Cu) from Waste Stabilization Pond and Constructed Wetland

Hydraulic resident time (Weeks)	Inlet Concentration (mg/L)	Outlet Concentration (mg/L)		Removal efficiency (%)	
		WSP	CWS	WSP	CWS
1	0.17	0.156	0.077	8.25	55
2	0.192	0.175	0.083	9.1	57
3	0.25	0.227	0.155	9.16	62
4	0.213	0.195	0.076	8.62	75
5	0.15	0.136	0.035	9.60	77
6	0.19	0.171	0.034	9.91	85
7	0.198	0.180	0.028	8.9	86.5
8	0.21	0.189	0.022	9.87	89.5
9	0.245	0.222	0.067	9.52	89.8
10	0.195	0.178	0.02	8.89	90

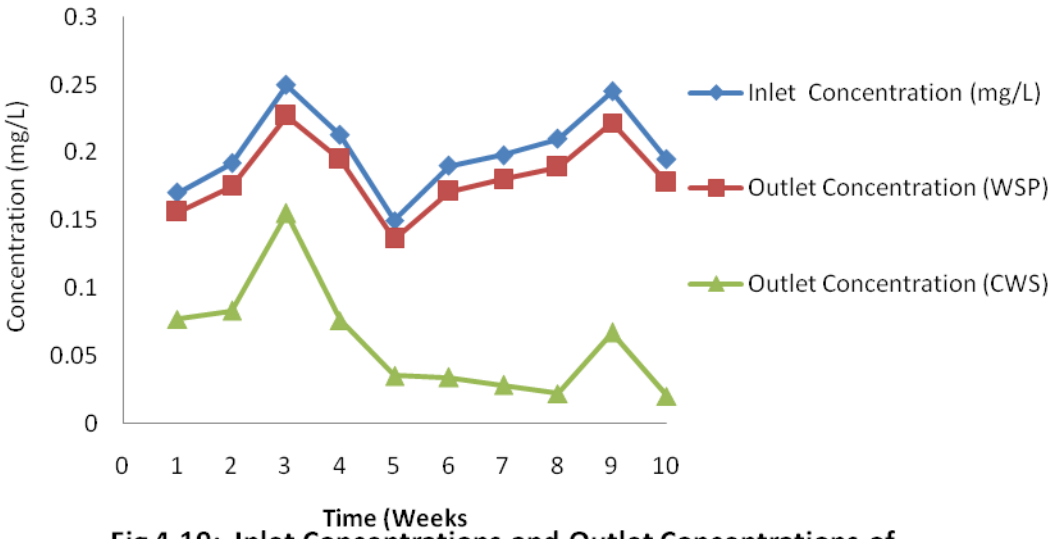


Fig 4.19: Inlet Concentrations and Outlet Concentrations of the Copper (C) from Waste Stabilization Pond and Constructed Wetland

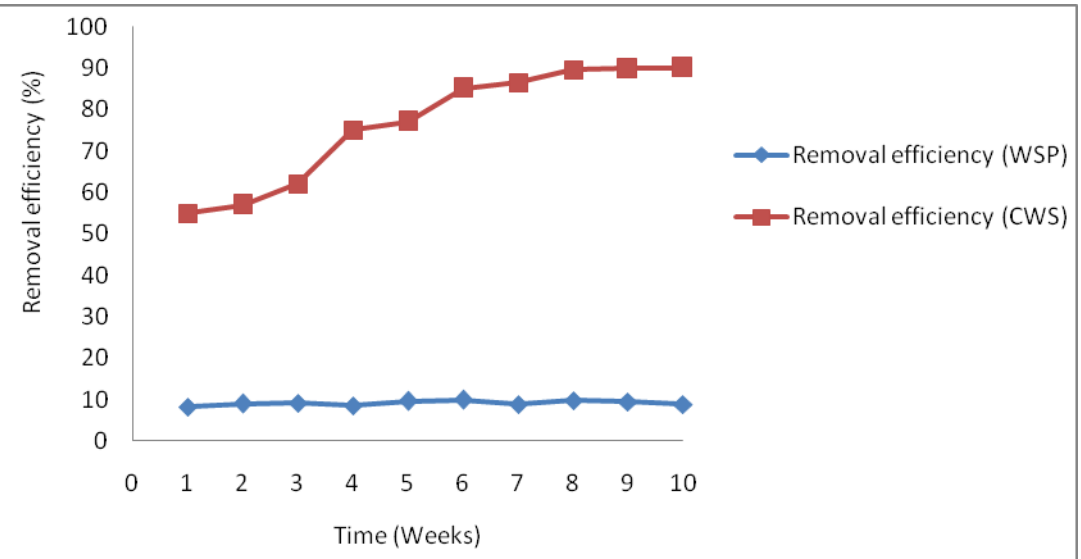


Fig 4.20: Removal Efficiencies of the Copper (Cu) from Waste Stabilization Pond and Constructed Wetland

The removal of Copper (Cu) by the constructed wetland and waste stabilization pond ranged from 55 – 90 % and 8.25 – 9.91% respectively after 7 days retention time for the period of ten (10) weeks of the study. Similarly, the study carried out by Gersberg *et al.*, (1986b) revealed that the maximum removal of Cu in a constructed wetland planted with a water hyacinth at hydraulic retention times of 5.5 days is 99%. However, different plants have different capacities to remove heavy metals (Kadlec *et al.*, 2000). Chemical precipitation is enhanced by wetland metabolism, especially of algal cells which deplete dissolved CO_2 levels and raise the pH (Reed *et al.*, 1995).

The above is a discussion of the influence of the constructed wetland and the waste stabilization pond on individual heavy metals assessed in this study. Subsequently, these observations were subjected to statistical assessment using IBM SPSS Statistics 22 and the results are shown in Table 4.11 (a-f).

Table 4.11a: Case Processing Summary

	Cases					
	Included		**Excluded**		**Total**	
	N	Percent	N	Percent	N	Percent
WSP * Heavy metals	100	100.0%	0	0.0%	100	100.0%
CWS * Heavy metals	100	100.0%	0	0.0%	100	100.0%

Table 4.11b: Report

Heavy Metals		WSP	CWS
Lead (Pb)	Sum	7.4110	2.1640
	Mean	.741100	.216400
	Std. Deviation	.0539762	.1033163
Zinc (Zn)	Sum	7.8080	3.9480
	Mean	.780800	.394800
	Std. Deviation	.0804830	.1454180
Manganese (Mn)	Sum	7.8660	2.4340
	Mean	.786600	.243400
	Std. Deviation	.0527072	.1391667
Magnesium (Mg)	Sum	36.3050	13.2060
	Mean	3.630500	1.320600
	Std. Deviation	.1694411	.4264776
Silver (Ag)	Sum	1.8640	.8680
	Mean	.186400	.086800
	Std. Deviation	.0170893	.0214414
Cobalt (Co)	Sum	.1010	.0600
	Mean	.010100	.006000
	Std. Deviation	.0076223	.0054569
Chromium (Cr)	Sum	8.4720	2.9780
	Mean	.847200	.297800
	Std. Deviation	.0322862	.1086082
Cadmium (Cd)	Sum	1.1130	.4420
	Mean	.111300	.044200
	Std. Deviation	.0076891	.0155835
Iron (Fe)	Sum	93.9730	47.8770
	Mean	9.397300	4.787700
	Std. Deviation	.3403332	.9723700
Copper (Cu)	Sum	1.8290	.5970
	Mean	.182900	.059700
	Std. Deviation	.0275215	.0415212
Total	Sum	166.7420	74.5740
	Mean	1.667420	.745740
	Std. Deviation	2.7780881	1.4404696

Table 4.11c: ANOVA Table

			Sum of Squares	df	Mean Square	F	Sig.
WSP * Heavy metals	Between Groups	(Combined)	762.629	9	84.737	5332.195	.000
	Within Groups		1.430	90	.016		
	Total		764.060	99			
CWS * Heavy metals	Between Groups	(Combined)	194.685	9	21.632	181.348	.000
	Within Groups		10.735	90	.119		
	Total		205.420	99			

Table 4.11d: Report of weekly sampling

Weekly Sample Collected		WSP	CWS
1	Sum	16.5430	9.6670
	Mean	1.654300	.966700
	Std. Deviation	2.8387702	1.8116553
2	Sum	17.5940	9.5830
	Mean	1.759400	.958300
	Std. Deviation	3.0754699	1.7274103
3	Sum	16.9560	9.2950
	Mean	1.695600	.929500
	Std. Deviation	2.9626635	1.7895307
4	Sum	17.2450	8.8220
	Mean	1.724500	.882200
	Std. Deviation	3.0479642	1.7208092
5	Sum	16.3710	7.7610
	Mean	1.637100	.776100
	Std. Deviation	2.8532288	1.5311589
6	Sum	16.5660	7.3970
	Mean	1.656600	.739700
	Std. Deviation	2.8942705	1.4568612
7	Sum	16.0240	6.4960
	Mean	1.602400	.649600
	Std. Deviation	2.8004369	1.3684345
8	Sum	16.7960	5.9280
	Mean	1.679600	.592800
	Std. Deviation	2.9634167	1.2316857
9	Sum	16.5590	5.0720
	Mean	1.655900	.507200
	Std. Deviation	2.9160891	1.0997590
10	Sum	16.0880	4.5530
	Mean	1.608800	.455300
	Std. Deviation	2.7642841	.9858355
Total	Sum	166.7420	74.5740
	Mean	1.667420	.745740
	Std. Deviation	2.7780881	1.4404696

Table 4.11e: ANOVA Table

			Sum of Squares	df	Mean Square	F	Sig.
WSP * Weekly Sample Collected	Between Groups	(Combined)	.217	9	.024	.003	1.000
	Within Groups		763.843	90	8.487		
	Total		764.060	99			
CWS * Weekly Sample Collected	Between Groups	(Combined)	3.212	9	.357	.159	.997
	Within Groups		202.208	90	2.247		
	Total		205.420	99			

Table 4.11f : Correlations

				INLET	**WSP**	**CWS**
INLET	Pearson Correlation			1	.999**	.971**
	Sig. (2-tailed)				.000	.000
	N			100	100	100
	Bootstrap[b]	Bias		0	.000	.001
		Std. Error		0	.000	.007
		95% Confidence Interval	Lower	1	.998	.956
			Upper	1	1.000	.984
WSP	Pearson Correlation			.999**	1	.972**
	Sig. (2-tailed)			.000		.000
	N			100	100	100
	Bootstrap[b]	Bias		.000	0	.001
		Std. Error		.000	0	.007
		95% Confidence Interval	Lower	.998	1	.958
			Upper	1.000	1	.985
CWS	Pearson Correlation			.971**	.972**	1
	Sig. (2-tailed)			.000	.000	
	N			100	100	100
	Bootstrap[b]	Bias		.001	.001	0
		Std. Error		.007	.007	0
		95% Confidence Interval	Lower	.956	.958	1
			Upper	.984	.985	1

**. Correlation is significant at the 0.01 level (2-tailed).

b. Unless otherwise noted, bootstrap results are based on 100 bootstrap samples

The relationship between waste stabilization pond and constructed wetland effluents are highly and positively correlated. There was statistically significant difference at the $p < 0.01$ level in removal efficiencies of heavy metals for WSP and CW $F(9, 181.348) = 21.632$, $p=0.01$. In addition to reaching statistical significant, the actual difference in mean values between WSP and CW was significant too (i.e. Mean for WSP and CW = 1.667420 and 0.745740 respectively). This study observed that the constructed wetland significantly removed heavy metals more than waste stabilization pond.

4.12 pH value

The pH readings of inlet and outlet of wastewater from waste stabilization pond and constructed wetland are shown in Table 4.12. The data are presented graphically in Figure 4.21.

Table 4.12: pH Readings of Inlet and Outlet Wastewater from Waste Stabilization Pond and Constructed Wetland

Hydraulic resident time (Weeks)	**PARAMETERS**				
	Inlet Readings	**Outlet Readings**		**FAO (1985)**	**WHO (1994)**
		WSP	**CWS**		
1	6.8	7.61	7.4		
2	6.55	7.58	7.15		
3	6.73	7.64	7.33		
4	6.52	7. 56	7.12		
5	6.24	6.8	6.84		
6	6.55	6.86	7.15		
7	6.61	7.41	7.21	6.0-8.4	6.0-8.5
8	6.31	6.8	6.9		
9	6.62	7.28	7.22		
10	6.72	7.25	7.73		

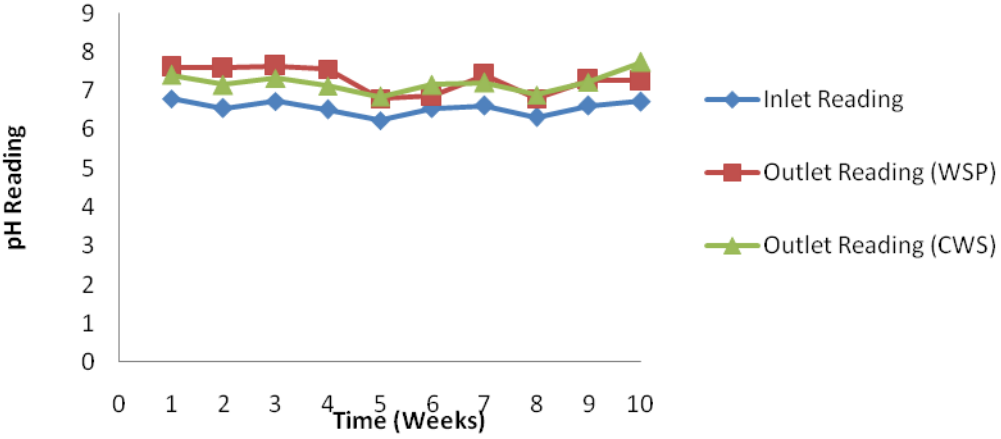


Fig 4.21: pH reading of Inlet Concentration, Outlet Concentration from Waste Stabilization Pond and Constructed Wetland

The pH of influent wastewater varied from 6.24 - 6.80 with an average of 6.57 while that of the effluents from constructed wetland and waste stabilization pond varied from 6.84 - 7.4 with an average of 7.16 and from 6.80 - 7.64 with an average of 7.28 respectively. The values of pH ranged in a narrow interval from 6.80 – 7.64, which suggests a slightly acidic to slightly alkaline conditions for the both systems. The pH of influent wastewater has no significant variation in comparison with that of effluent from the constructed wetland and waste stabilization pond. The pH of effluent from constructed wetland and that of waste stabilization pond are circum-neutral. Usually, wetland waters have a pH of about 6-8 (Kadlec and Knight, 1996) and pH of effluent from constructed wetland and waste stabilization pond falls within the range. This is also within World Health Organzation, WHO (1984), and Food and Agriculture Organization, FAO (1994) permissible limits of good water quality for irrigation (6.0 – 8.5) from appendix I and II. It was observed that pH inlet wastewater was slightly lower than that of outlet wastewater from both

constructed wetland and waste stabilization pond. The observed difference probably would have been caused by plant photosynthesis that occurred during the day (Sawyer and McCarty, 1978).

4.13 Temperature

The temperature readings of inlet and outlet wastewater of the constructed wetland and waste stabilization pond are shown in Table 4.13. The data is presented graphically in Figure 4.22.

Table 4.13: Temperature of Inlet and Outlet from Waste Stabilization Pond and Constructed Wetland

Hydraulic resident time (Weeks)	PARAMETERS		
	Inlet Readings (T ^{o}C)	Outlet Readings (T ^{o}C)	
		WSP	CWS
1	27.82	27.82	27.89
2	27.91	27.92	27.95
3	27.98	27.98	28.03
4	27.86	27.86	27.93
5	28.01	28.02	28.08
6	27.98	27.98	28.05
7	27.96	27.96	28.04
8	28.06	28.06	28.11
9	28.02	28.2	28.09
10	27.99	27.99	28.08

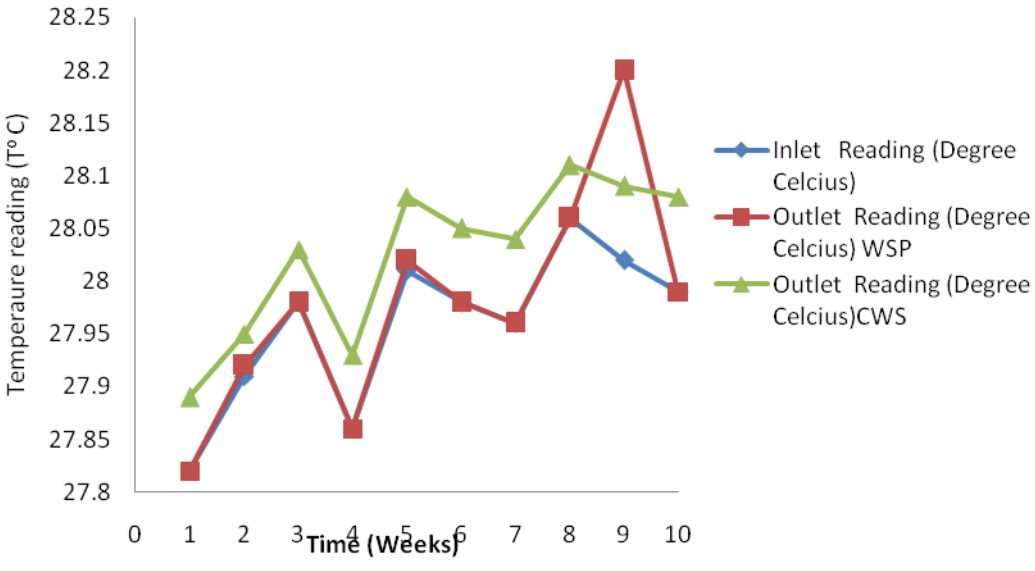


Fig 4.22: Temperature reading of Inlet Concentration and Outlet Concentration from Waste Stabilization Pond and Constructed Wetland

The temperature of influent wastewater ranged from 27.82 - 28.01^{o}C with an average of 27.96^{o}C, while that of effluents from constructed wetland and waste stabilization pond ranged from 27.89 - 28.11^{o}C with an average of 28.03^{o}C and from 27.82 – 28.20 with an average of 27.98^{o}C respectively. Temperature affects aquatic life, micro-organisms and solubility of oxygen in wastewater (El-Monayeri *et al*., 2007). According to Metcalf and Eddy (1995), the optimum temperature for bacterial activity ranges from 25^{o}C to 35^{o}C, while the nitrifying bacteria and some aerobic bacteria stop action at 50^{o}C. The temperature of effluent wastewater from the constructed wetland cell was slightly higher than that of the influent as a result of retention of heat from the sun during the day time until the early hours of the morning by the filter media of the sub-surface horizontal flow constructed wetland. However, temperatures of inlet and outlet of wastewater of the waste stabilization

pond seem to be more or less constant, which were quite close to the ambient air temperature of the surrounding environment.

4.14 Total Suspended Solids (TSS) removal

The results of removal efficiencies of Total Suspended Solids by the constructed wetland and waste stabilization pond are shown in Table 4.14. The inlet concentrations, outlet concentrations of the Total Suspended Solids (TSS) in waste stabilization pond and constructed wetland is presented graphically in Figure 4.23, while the removal efficiency of Total Suspended Solids from waste stabilization pond and constructed wetland is shown in Figure 4.24.

Table 4.14: Inlet and Outlet Concentrations and Removal Efficiencies of the Total Suspended Solids (TSS) from Waste Stabilization Pond and Constructed Wetland

Hydraulic resident time (Weeks)	Inlet Concentration (mg/L)	Outlet Concentration (mg/L)		Removal efficiency (%)	
		WSP	CWS	WSP	CWS
1	165	57.75	26.4	65	84
2	211	63.3	27.43	70	87
3	156	45.24	18.72	71	88
4	182	43.68	20.02	76	89
5	173	37.89	18.68	78.1	89.2
6	169	36.17	17.75	78.6	89.5
7	178	42.72	26.7	76	85
8	186.4	41.01	26.84	78	85.6
9	164	36.9	22.8	77.5	86.1
10	168	50.74	22.85	69.8	86.4

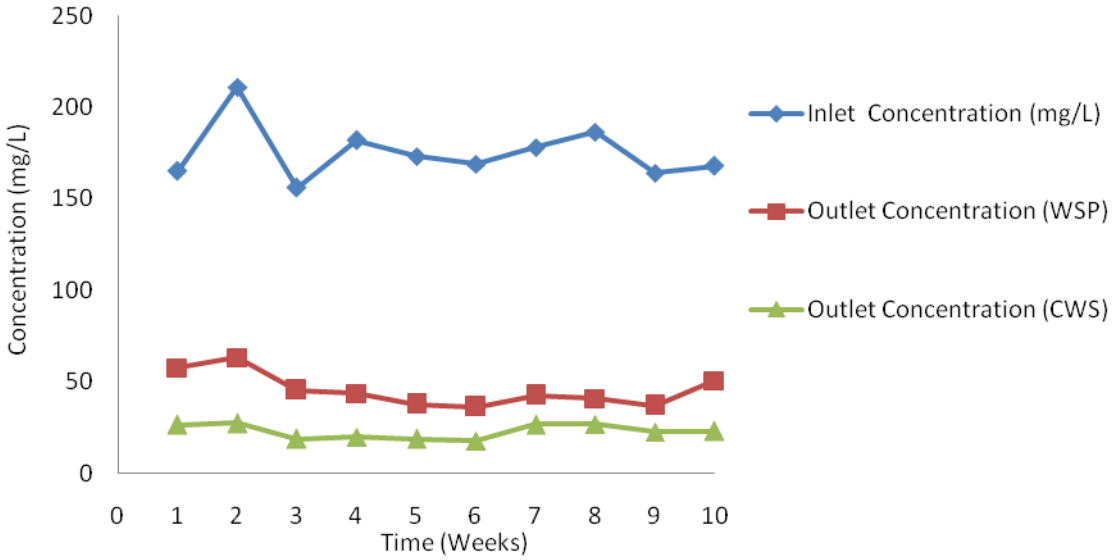


Fig 4.23: Inlet Concentrations, Outlet Concentrations of the Total Suspeded Solid (TSS) from Waste Stabilization Pond and Constructed Wetland

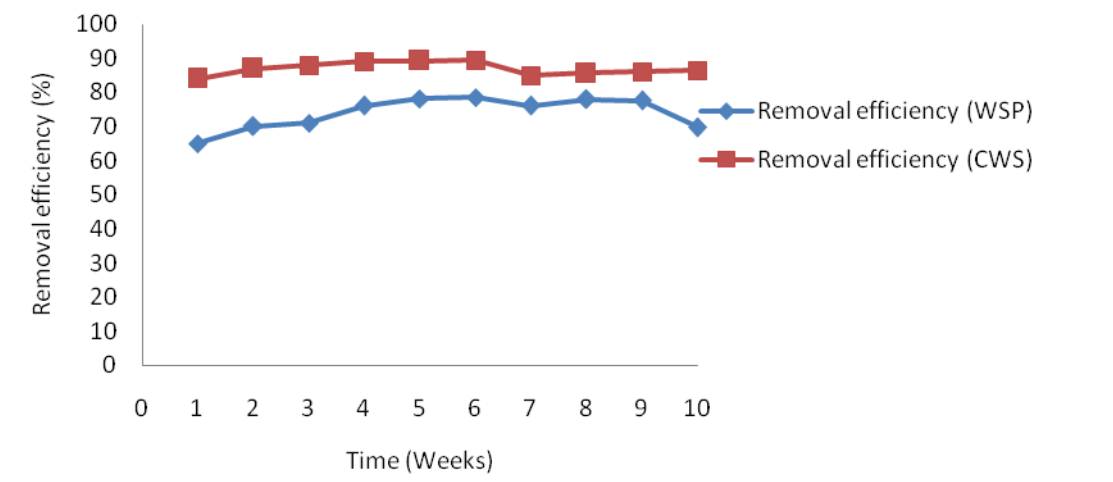


Fig 4.24: Removal Efficiencies of the Total Suspended Solid (TSS) from Waste Stabilization Pond and Constructed Wetland

The TSS removal efficiency by constructed wetland and waste stabilization pond ranged from 84 – 89.2% and 65 -78.6% respectively during 7 days retention time for a period of

ten (10) weeks. Similar to this study, Rai *et al*., (2013) found constructed wetland to remove more than 65% of TSS from inlet wastewater after 36 h retention time under fully established condition while. Zhang *et al.,* (2012) reported 79.93% of TSS removal efficiency from constructed wetland.

4.15 Faecal Coliform (FC) removal

The results of removal efficiencies of faecal coliforms by the constructed wetland and waste stabilization pond are shown in Table 4.15. The inlet concentrations, outlet concentrations of faecal coliforms in waste stabilization pond and constructed wetland is presented graphically in Figure 4.25, while the removal efficiency of faecal coliforms from waste stabilization pond and constructed wetland is shown in Figure 4.26.

Table 4.15: Inlet and Outlet Coliform Densities and Removal Efficiencies of Faecal Coliforms (FC) from Constructed Wetland and Waste Stabilization Pond

Hydraulic resident time (Weeks)	Inlet Concentration (mg/L)	Outlet Concentration (mg/L)		Removal efficiency (%)	
		WSP	CWS	WSP	CWS
1	3.8×10^4	1.22×10^4	4.56×10^3	68	88
2	3.4×10^4	8.5×10^3	3.74×10^3	75	87
3	2.9×10^4	7.5×10^3	3.19×10^3	74	88
4	3.5×10^4	7.35×10^3	4.2×10^3	79	88
5	3.1×10^4	6.14×10^3	3.41×10^3	80.2	89
6	2.8×10^4	5.94×10^3	3.02×10^3	78.8	89.2
7	3.6×10^4	7.42×10^3	2.84×10^3	79.4	92.1
8	2.6×10^4	5.33×10^3	1.9×10^3	79.5	92.7
9	2.61×10^4	4.93×10^3	1.8×10^3	81.1	93.1
10	3.66×10^4	7.10×10^3	2.08×10^3	80.6	94.3

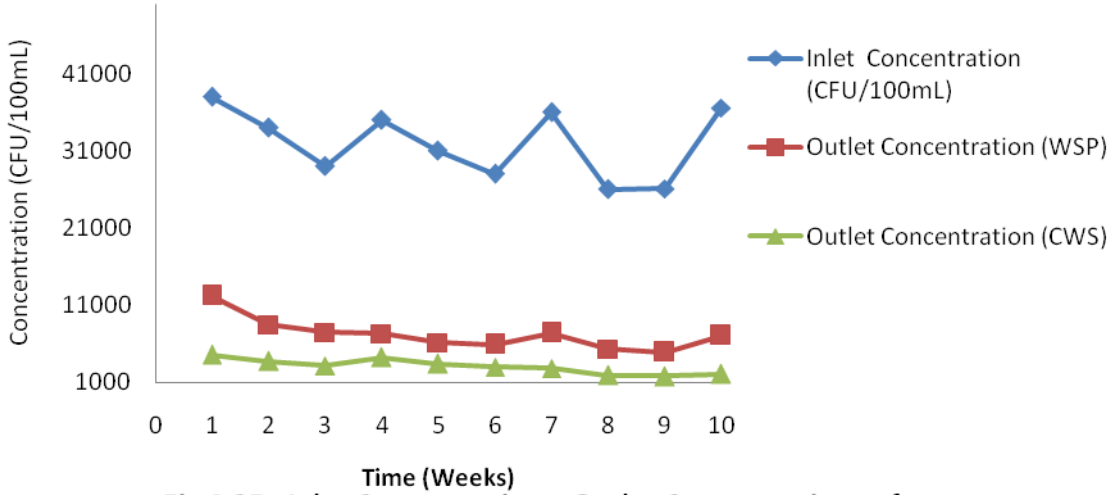


Fig 4.25: Inlet Concentrations, Outlet Concentrations of the Faecal Coliforms (FC) from Waste Stabilization Pond and Constructed Wetland

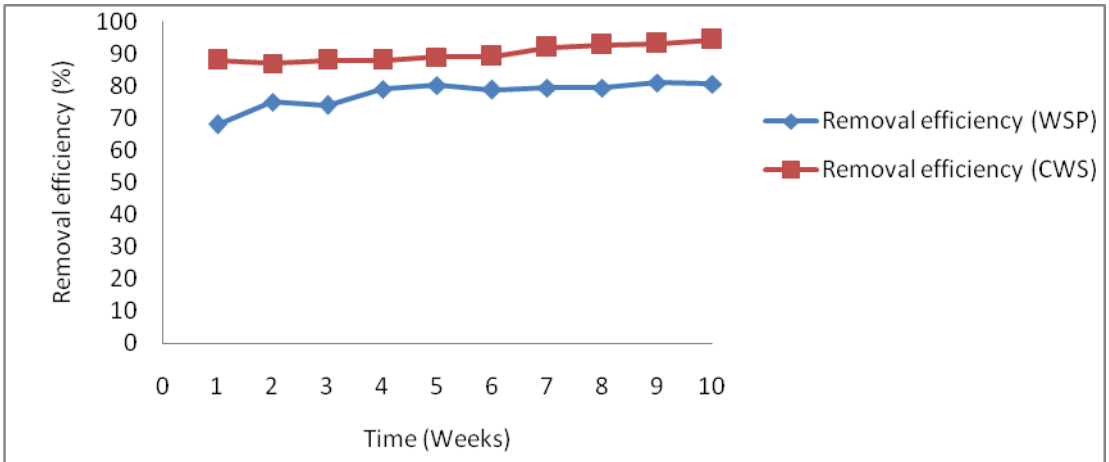


Fig 4.26: Removal Efficiencies of the Faecal Coliforms (FC) from Waste Stabilization Pond and Constructed Wetland

The FC removal efficiency by constructed wetland and waste stabilization pond ranged from 87- 94.3% and 68- 81.1% respectively during 7 days retention time for a period of ten

(10) weeks. It was observed that the FC removal efficiency increases as the hydraulic resident time increases. A high reduction in faecal coliforms and high pathogen removal in constructed wetlands could be attributed to the damage of their cytoplasmic contents caused by sunlight penetration (Awuah *et al.*, (2002) and Davies-Colley *et al.*, (1997).

4.16 Dissolved Oxygen (DO) Improvement

The DO readings of inlet and outlet of wastewater from constructed wetland and waste stabilization pond are shown in Table 4.16. The inlet concentrations, outlet concentrations of Dissolved Oxygen (DO) in waste stabilization pond and constructed wetland is presented graphically in Figure 4.27, while the removal efficiency of Dissolved Oxygen from waste stabilization pond and constructed wetland is shown in Figure 4.28.

Table 4.16: Inlet and Outlet Concentrations of Dissolved Oxygen (DO) and Increased DO by Waste Stabilization Pond and Constructed Wetland

Hydraulic resident time (Weeks)	Inlet Concentration (mg/L)	Outlet Concentration (mg/L)		Improvement efficiency (%)	
		WSP	CWS	WSP	CWS
1	1..8	2.21	2.7	18.55	33.58
2	1.84	2.12	3.15	13.21	41.59
3	1.76	2.23	3.64	21.08	51.65
4	1.78	2.18	4.1	18.35	56.59
5	1.76	2.19	4.26	19.63	58.69
6	1.79	2.17	4.38	17.57	59.13
7	1.78	2.12	4.48	16.04	60.27
8	1.82	2.18	4.6	16.51	60.43
9	1.78	2.15	4.69	17.21	62.05

10	1.76	2.19	4.7	19.63	62.55

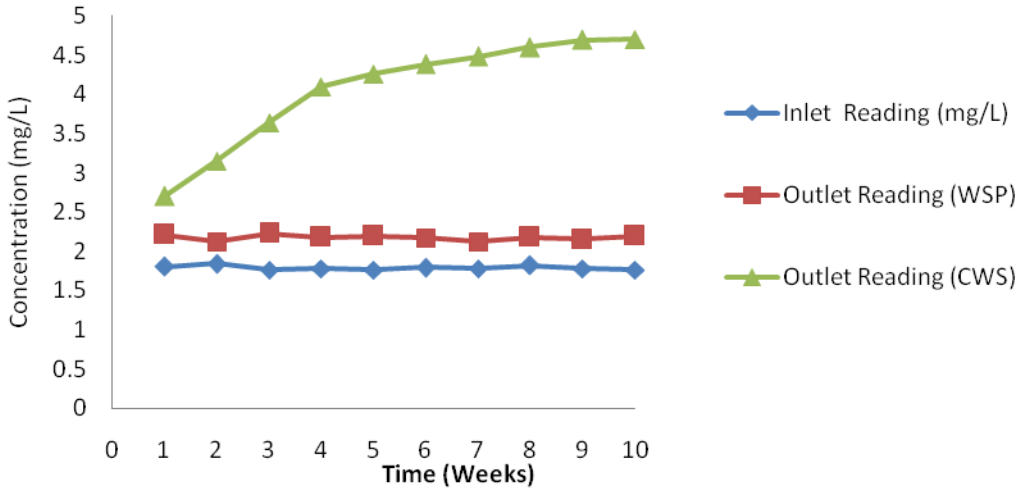


Fig 4.27: Inlet Concentrations, Outlet Concentrations of the Dissolved Oxygen (DO) from Waste Stabilization Pond and Constructed Wetland

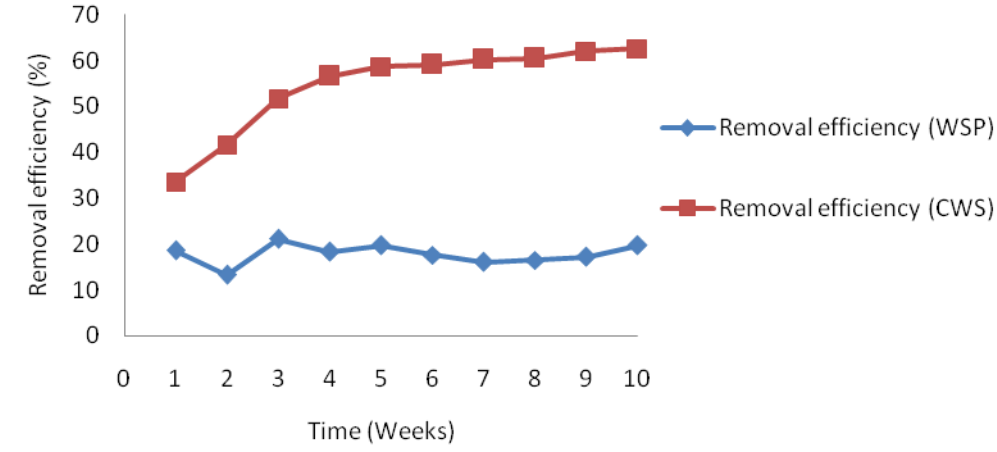


Fig 4.28: Removal Efficiencies of the Dissolved Oxygen (DO) from Waste Stabilization Pond and Constructed Wetland

The DO of influent wastewater varied from 1.76 – 1.80mg/L, while DO readings of effluent from constructed wetland and waste stabilization pond varied from 2.70 - 4.70mg/L and 2.12 – 2.23mg/L respectively during 7 days retention time for a period of ten (10) weeks. It is observed that the DO increases as the hydraulic resident time increases. Similar study by Rai *et al*., (2013) reported that DO increased from 0 - 4.71 mg/L at 36 h in a fully established constructed wetland. This is probably as a result of oxygen release by exudation into the root zone around sediments, a phenomenon similar to what UNEP (2011) attributed to hollow stem features of wetland plants for passage of oxygen to root tissues.

4.17 Biochemical Oxygen Demand (BOD)

The biochemical oxygen demand removal efficiency of the constructed wetland and waste stabilization pond are shown in Table 4.17. The inlet concentrations, outlet concentrations of biochemical oxygen demand in waste stabilization pond and constructed wetland is presented graphically in Figure 4.29, while the removal efficiency of biochemical oxygen demand from waste stabilization pond and constructed wetland is shown in Figure 4.30.

Table 4.17: Inlet and Outlet Concentrations and Removal Efficiencies of the Biochemical Oxygen Demand (BOD) from Constructed Wetland and Waste Stabilization Pond.

Hydraulic resident time (Weeks)	Inlet Concentration (mg/L)	Outlet Concentration (mg/L)		Removal efficiency (%)	
		WSP	CWS	WSP	CWS
1	156	40.56	34.32	70	78
2	190	55.1	30.4	71	84
3	185	51.8	24.05	72	87
4	276	82.8	30.36	70	89
5	198	50.69	18.61	74.4	90.6
6	176.5	41.83	15.53	76.3	91.2
7	172.6	39.35	14.15	77.2	91.8
8	176.8	38.72	14.14	78.1	92
9	189	41.01	13.61	78.3	92.8
10	210	46.41	14.7	77.9	93

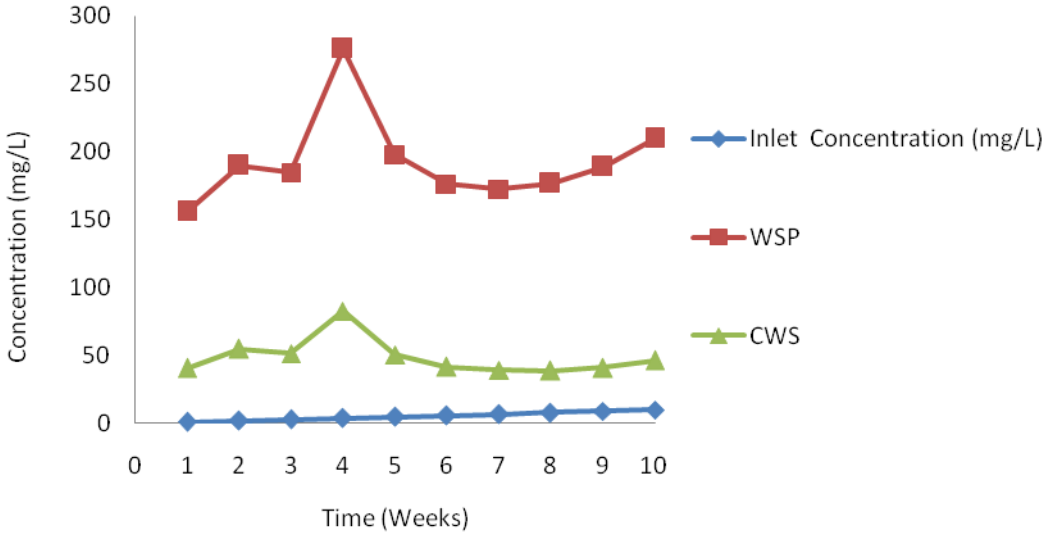


Fig 4.29: Inlet Concentrations and Outlet Concentrations of the Biochemical Oxygen Demand (BOD) from Waste Stabilization Pond and Constructed Wetland

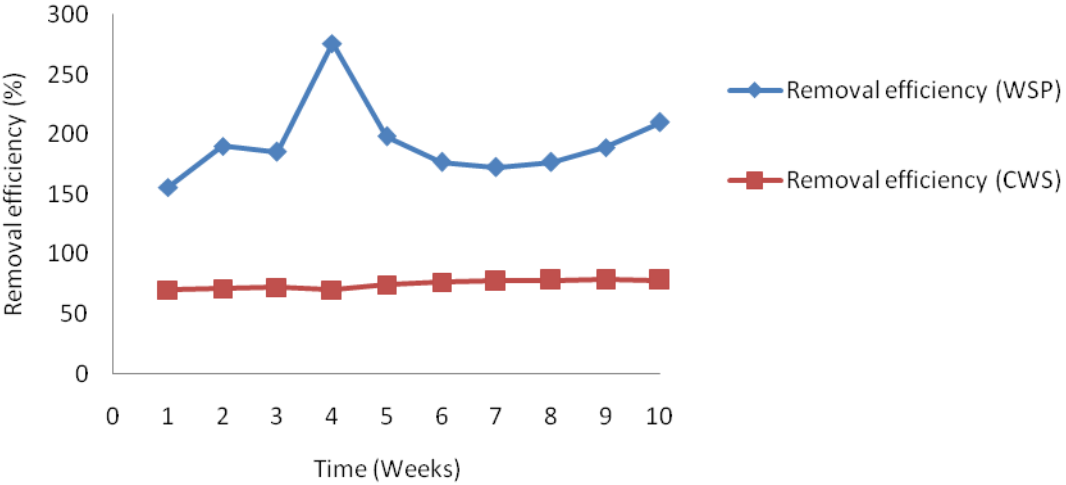


Fig 4.30: Removal Efficiencies of the Biochemical Oxygen Demand (BOD) from Waste Stabilization Pond and Constructed Wetland

The BOD removal efficiency by constructed wetland and waste stabilization pond ranged from 78 – 93% and 70- 78.3% respectively during the ten (10) weeks study period. It was observed that the BOD removal efficiency increased as the hydraulic resident time increased. This agrees with results of other researchers like Vymazal (2010); Zhang *et al.*, (2010); Baskar *et al*. (2014) and Karathanasis *et al.* (2003). According to Zhang *et al*., (2009), the high removal rates of BOD are caused by sedimentation of suspended solids and by rapid decomposition processes in the water and upper soil layers.

4.18 Chemical Oxygen Demand (COD)

The results of removal efficiency of chemical oxygen demand by constructed wetland and waste stabilization pond are shown in Table 4.18. The inlet concentrations, outlet concentrations of chemical oxygen demand in waste stabilization pond and constructed wetland is presented graphically in Figure 4.31, while the removal efficiency of chemical oxygen demand from waste stabilization pond and constructed wetland is shown in Figure 4.32.

Table 4.18: Inlet and Outlet Concentrations and Removal Efficiencies of the Chemical Oxygen Demand (COD) by Constructed Wetland and Waste Stabilization Pond

Hydraulic resident time (Weeks)	Inlet Concentration (mg/L)	Outlet Concentration (mg/L)		Removal efficiency (%)	
		WSP	CWS	WSP	CWS
1	410	147.6	131.2	64	68
2	430	133.3	124.7	69	71
3	402	132.66	96.48	67	76
4	595	184.45	136.85	69	77
5	451	136.2	94.71	69.8	79
6	352	111.23	76.74	68.4	78.2
7	389	135.76	83.25	65.1	78.6
8	392	136.42	81.93	65.2	79.1
9	348	114.49	69.25	67.1	80.1
10	418	136.27	81.51	67.4	80.5

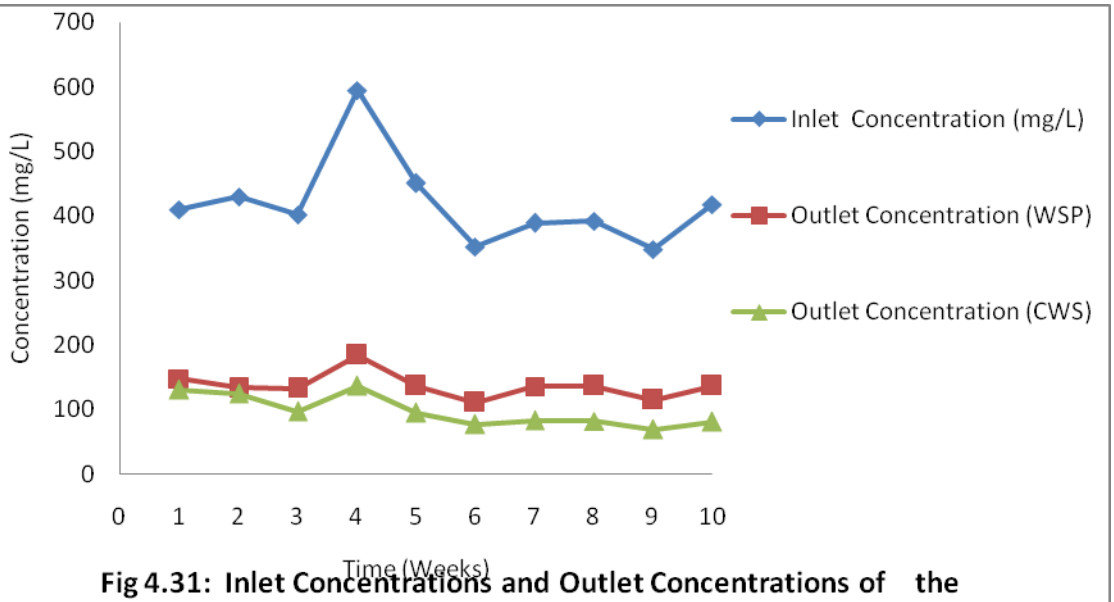


Fig 4.31: Inlet Concentrations and Outlet Concentrations of the Chemical Oxygen Demand (COD) from Waste Pond and Constructed Wetland

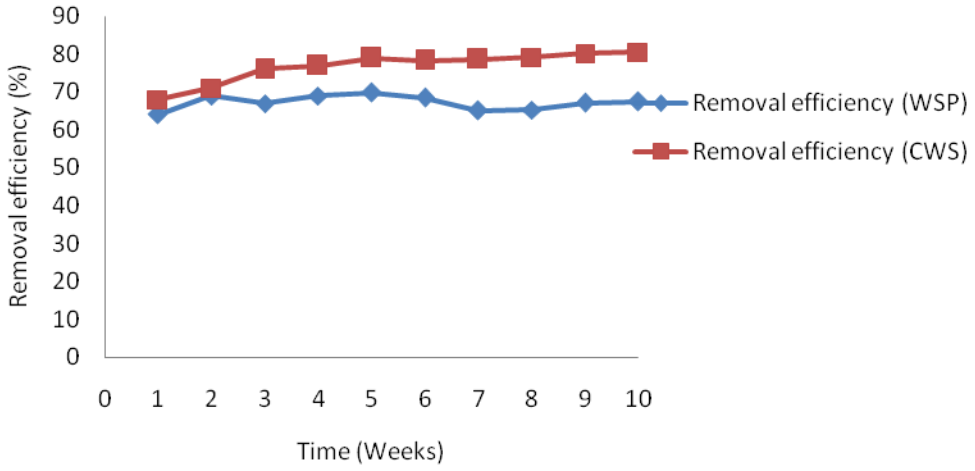


Fig 4.32: Removal Efficiencies of the Chemical Oxygen Demand (COD) from Waste Stabilization Pond and Constructed Wetland

The COD removal efficiency by constructed wetland and waste stabilization pond ranged from 68 – 80.5% and 64- 69.8% respectively during 7 days retention time for a period of ten (10) weeks. The COD removal is believed to occur rapidly through settling and entrapment of particulate organic matter in the void spaces of the substrate in the constructed wetland (Reed *et al.,* 1988). The substrate is the main supporting material for plants and microbial growth while fine gravel promotes higher growth of plants and therefore increases the quantity of contaminant removal (USEPA, 1988).The researchers Zhang *et al.,* (2014) and Golda *et al*., (2014) in similar research works reported COD maximum removal efficiency of 82% and 77.8% respectively.

4.19 Phosphate (PO_4)

The results of removal efficiency of phosphate by the constructed wetland and waste stabilization pond are shown in Table 4.19. The inlet concentrations, outlet concentrations of phosphate in waste stabilization pond and constructed wetland is presented graphically in Figure 4.33, while the removal efficiency of phosphate from waste stabilization pond and constructed wetland is shown in Figure 4.34.

Table 4.19: Inlet and Outlet Concentrations and Removal Efficiencies of the Phosphates (PO_4) from Waste Stabilization Pond and Constructed Wetland

Hydraulic resident time (Weeks)	Inlet Concentration (mg/L)	Outlet Concentration (mg/L)		Removal efficiency (%)		Parameters for Irrigation	
						FAO (1985) (mg/L)	WHO (1994) (mg/L)
		WSP	CWS				
1	6.2	4.71	4.05	24.1	34.7		
2	6.41	4.61	4.11	28.06	35.86		
3	5.98	4.14	3.7	30.8	38.08		
4	6.85	4.66	3.97	32	42.02		
5	5.94	3.99	3.25	32.8	45.3		
6	5.97	3.94	2.99	34.03	49.8		
7	5.94	3.86	2.77	35.02	53.4	0-2.0	0-2.0
8	6.29	4.02	2.52	36.12	60		
9	6.15	3.84	2.21	37.62	64		
10	6.2	3.84	2.02	38.12	67.5		

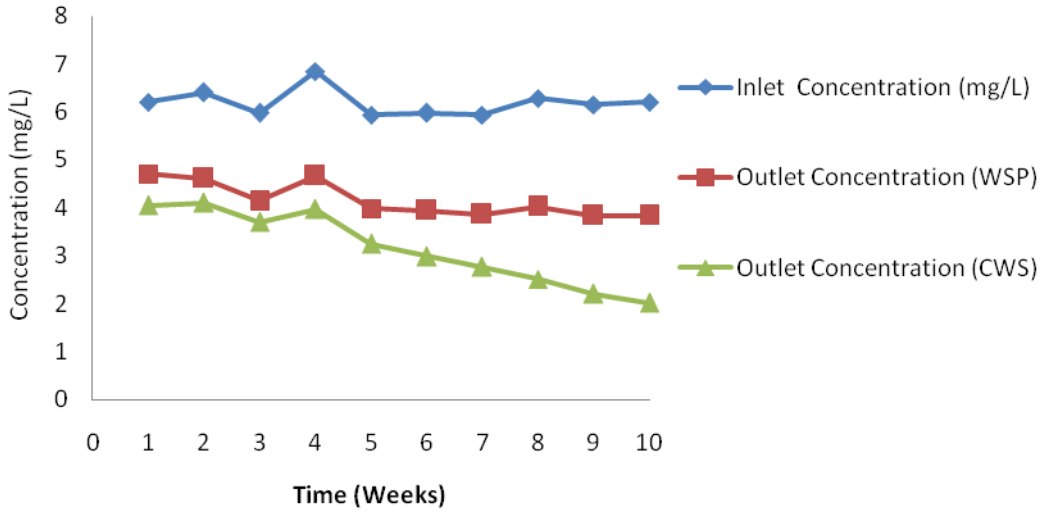


Fig 4.33: Inlet Concentrations and Outlet Concentrations of the Phosphate (PO_4-)from Waste Stabilization Pond and Constructed Wetland

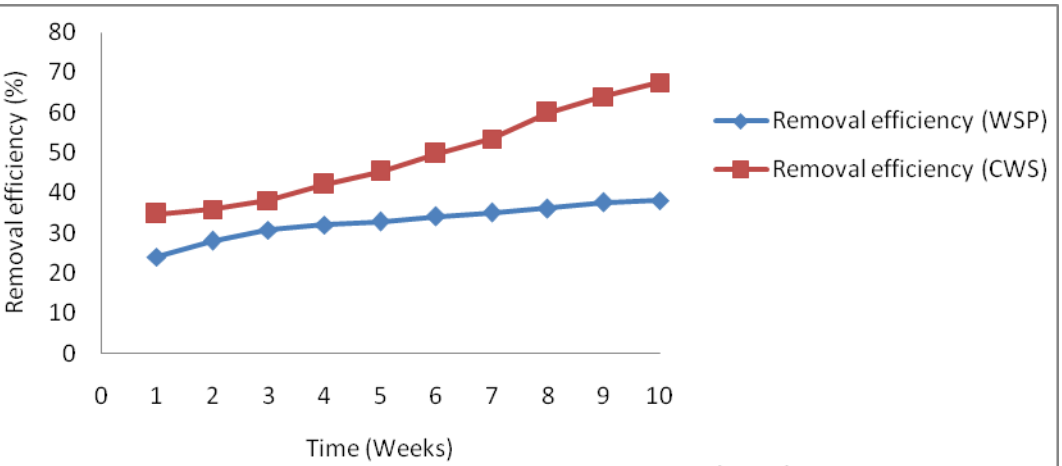


Fig 4.34: Removal Efficiencies of the Phosphate (PO_4-) from Waste Stabilization Pond and Constructed Wetland

The PO_4 removal efficiency by constructed wetland and waste stabilization pond ranged from 34.70 – 67.50% and 24.1– 38.12% respectively during the study period. These results are in conformity with the ones of similar studies carried out by Martinez-Guerra *et al.*,

(2015), Vymazal (2004), Klomjek *et al*., (2005) and Rai *et al*. (2015) with removal efficiency of phosphate of 60%, 60%, 36% and 71.1% respectively. It was observed that PO_4 removal efficiency increases as the hydraulic resident time increases.

4.20 Nitrate (NO_3)

The results of removal efficiency of Nitrate (NO_3) by constructed wetland and waste stabilization pond are shown in Table 4.20. The inlet concentrations, outlet concentrations of Nitrate in waste stabilization pond and constructed wetland is presented graphically in Figure 4.35, while the removal efficiency of Nitrate from waste stabilization pond and constructed wetland is shown in Figure 4.36.

Table 4.20: Inlet and Outlet Concentrations and Removal Efficiencies of the Nitrate (NO_3) from Waste Stabilization Pond and Constructed Wetland

Hydraulic resident time (Weeks)	Inlet Concentration (mg/L)	Outlet Concentration (mg/L)		Removal efficiency (%)		Parameters for Irrigation	
						FAO (1985) (mg/L)	WHO (1994) (mg/L)
		WSP	CWS				
1	8.92	2.85	2.5	66	72	5.0-30	5.0-50
2	8.47	2.8	2.2	67	74		
3	8.74	2.71	2.01	69	77		
4	7.88	2.29	1.5	71	81		
5	7.25	1.99	1.16	72.6	84		
6	7.82	2.24	1.14	71.4	85.4		
7	8.63	2.59	1.09	70	87.4		
8	7.28	2.26	0.83	68	88.6		
9	7.98	2.51	0.86	68.5	89.2		
10	8.16	2.56	0.85	68.6	89.6		

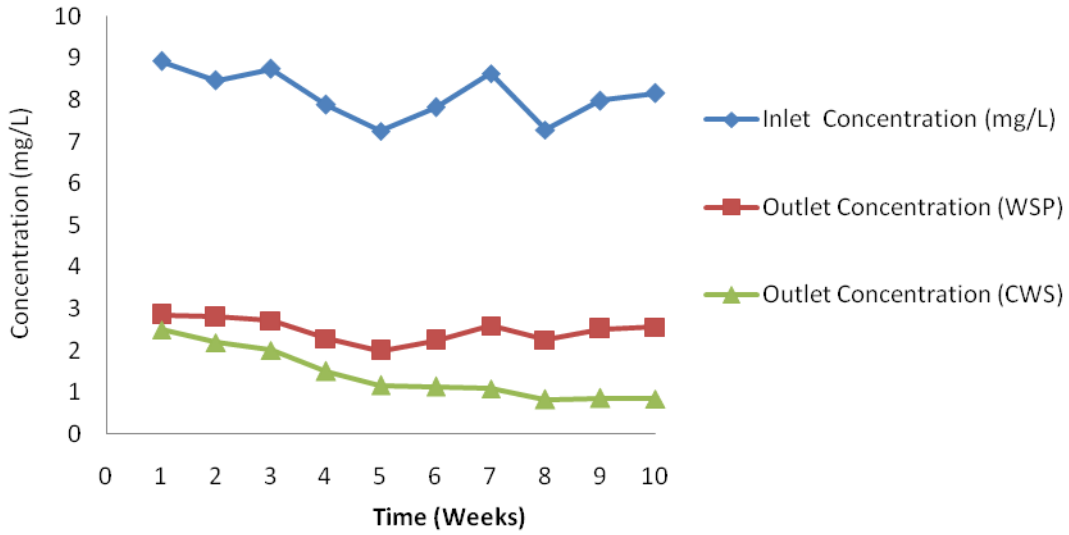


Fig 4.35: Inlet Concentrations and Outlet Concentrations of the Nitrate (NO_3-) from Waste Stabilization Pond and Constructed Wetland

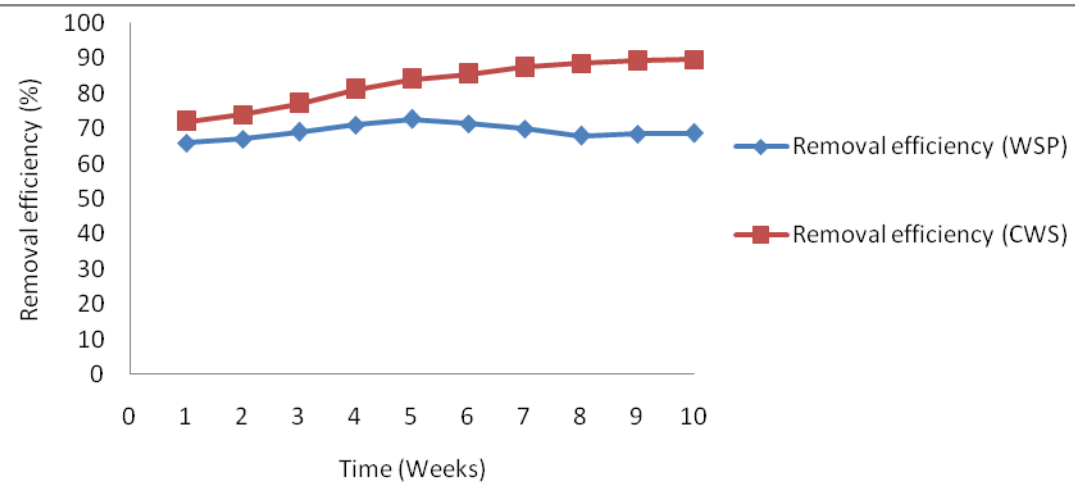


Fig 4.36: Removal Efficiencies of the Nitrate (NO_3-) from Waste Stabilization Pond and Constructed Wetland

The NO_3 removal efficiency by constructed wetland and waste stabilization pond ranged from 68 – 80.5% and 66- 72.6% respectively during 7 days retention time for a period of

ten (10) weeks. The researchers Truu *et al.,* (2009) in a similar study reported 89.6% of NO_3^- removal. It was observed that NO_3^- removal efficiency increases as the age of the aquatic plants. This may probably be attributed to the dense plant root system in constructed wetland which might have improved filtration and stimulated microbial activities especially nitrifying bacteria, leading to increased nutrient uptake (N, P) and biomass production (Korboulewsky *et al.*, 2012).

4.21 Ammonia (NH_4)

The results of removal efficiency of Ammonia (NH_4) by constructed wetland and waste stabilization pond are showed in Table 4.21. The inlet concentrations, outlet concentrations of Ammonia in waste stabilization pond and constructed wetland is presented graphically in Figure 4.37, while the removal efficiency of Ammonia from waste stabilization pond and constructed wetland is shown in Figure 4.38.

Table 4.21: Inlet and Outlet Concentrations and Removal Efficiencies of the Ammonia (NH_4) from Waste Stabilization Pond and Constructed Wetland

Hydraulic resident time (Weeks)	Inlet Concentration (mg/L)	Outlet Concentration (mg/L)		Removal efficiency (%)	
		WSP	CWS	WSP	CWS
1	18	15.8	14.97	12.2	16.83
2	16	13.94	13.04	12.86	18.48
3	17.2	14.79	13.76	14.02	20.02
4	16.8	14.28	13.3	14.98	20.84
5	16.1	13.55	12.55	15.84	22.08
6	17	14.29	12.91	15.92	24.04
7	14.6	12.14	10.89	16.82	25.43
8	16.3	13.55	11.68	16.9	28.37
9	17.3	14.36	12.04	17	30.4
10	15.8	13.11	10.6	17.02	32.92

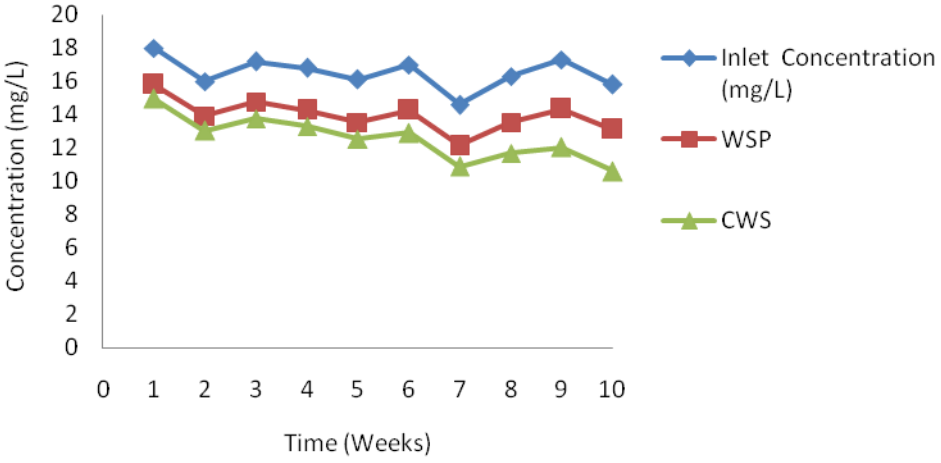


Fig 4.37: Inlet Concentrations, Outlet Concentrations of the Ammonia (NH_4-) from Waste Stabilization Pond and Constructed Wetland

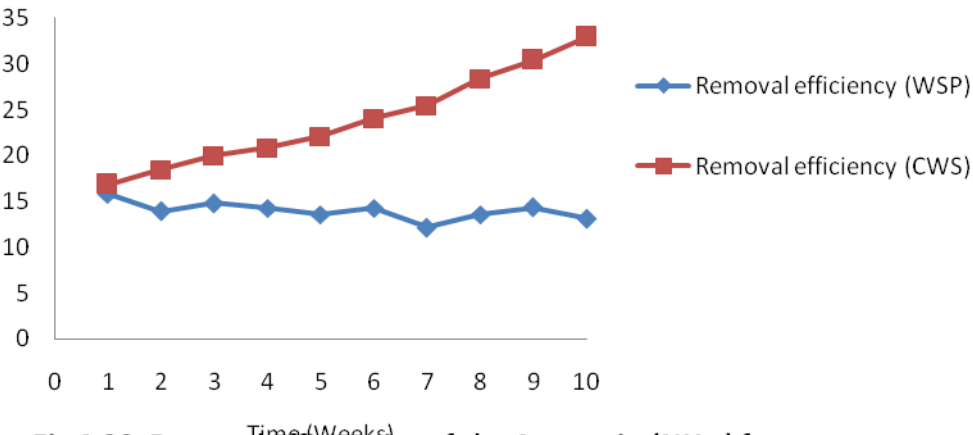


Fig 4.38: Removal Efficiencies of the Ammonia (NH_4-) from Waste Stabilization Pond and Constructed Wetland

The Ammonia (NH_4) removal efficiencies by constructed wetland and waste stabilization pond ranges from 16.83 - 32.92% and 12.2 - 17.02% respectively during 7 days retention time for a period of ten (10) weeks. It was observed that the Ammonia (NH_4) removal efficiency increases as the hydraulic resident time increases. The low percentage removal

of ammonia from the constructed wetland is similar to the research result obtained by Young *et al*., (2000) and this could probably as a result of limited uptake of ammonia by plants.

The above is a discussion of the influence of the constructed wetland and the waste stabilization pond on individual physico-chemical parameters assessed in this study. Subsequently, these observations were subjected to statistical assessment using IBM SPSS Statistics 22 and the results are shown in Table 4.22 (a-f).

Table 4.22a: Case Processing Summary

	Cases					
	Included		Excluded		Total	
	N	Percent	N	Percent	N	Percent
WSP * Physico-chemical parameters	100	100.0%	0	0.0%	100	100.0%
CWS * Physico-chemical parameters	100	100.0%	0	0.0%	100	100.0%

Table 4.22b: Report

Physico-chemical Parameters		WSP	CWS
Biochemical Oxygen Demand (BOD)	Sum	488.27	209.87
	Mean	48.8270	20.9870
	Std. Deviation	13.25828	8.07334
Chemical Oxygen Demand (COD)	Sum	1368.38	976.62
	Mean	136.8380	97.6620
	Std. Deviation	19.91640	24.41020
Total Suspended Solid (TSS)	Sum	455.40	228.19
	Mean	45.5400	22.8190
	Std. Deviation	9.09538	3.84099
Faecal Coliform (FC)	Sum	72.41	30.74
	Mean	7.2410	3.0740
	Std. Deviation	2.06034	.94828
Dissolved Oxygen (DO)	Sum	21.74	40.70
	Mean	2.1740	4.0700
	Std. Deviation	.03565	.68893
Ammonia (NH_4^-)	Sum	139.81	125.74
	Mean	13.9810	12.5740
	Std. Deviation	.98955	1.32590
Phosphate (PO_4^-)	Sum	41.61	31.59
	Mean	4.1610	3.1590
	Std. Deviation	.35701	.77768
Nitrate (NO_3^-)	Sum	24.80	14.14
	Mean	2.4800	1.4140
	Std. Deviation	.27765	.61196
pH	Sum	72.79	71.62
	Mean	7.2790	7.1620
	Std. Deviation	.34349	.17763
Temperature	Sum	279.79	280.25
	Mean	27.9790	28.0250
	Std. Deviation	.10567	.07546
Total	Sum	2965.00	2009.46
	Mean	29.6500	20.0946
	Std. Deviation	40.32436	28.61418

Table 4.22c: ANOVA Table

			Sum of Squares	Df	Mean Square	F	Sig.
WSP * Physico-chemical parameters	Between Groups	(Combined)	155032.801	9	17225.867	260.710	.000
	Within Groups		5946.570	90	66.073		
	Total		160979.371	99			
CWS * Physico-chemical parameters	Between Groups	(Combined)	74938.911	9	8326.546	122.460	.000
	Within Groups		6119.447	90	67.994		
	Total		81058.357	99			

Table 4.22d: Report of weekly sampling

Weekly Sample Collected		WSP	CWS
1	Sum	319.11	255.99
	Mean	31.9110	25.5990
	Std. Deviation	44.53257	38.93388
2	Sum	319.17	243.87
	Mean	31.9170	24.3870
	Std. Deviation	41.84891	37.00962
3	Sum	296.69	200.91
	Mean	29.6690	20.0910
	Std. Deviation	40.37571	28.42271
4	Sum	377.11	249.35
	Mean	37.7110	24.9350
	Std. Deviation	57.43342	40.67902
5	Sum	287.46	191.55
	Mean	28.7460	19.1550
	Std. Deviation	41.32471	27.94951
6	Sum	252.65	169.66
	Mean	25.2650	16.9660
	Std. Deviation	33.56851	22.63222
7	Sum	281.33	181.42
	Mean	28.1330	18.1420
	Std. Deviation	40.76320	24.82420
8	Sum	278.35	179.45
	Mean	27.8350	17.9450
	Std. Deviation	40.98135	24.53712
9	Sum	255.67	162.57
	Mean	25.5670	16.2570
	Std. Deviation	34.51102	20.74912
10	Sum	297.46	174.69
	Mean	29.7460	17.4690
	Std. Deviation	41.54527	24.30315
Total	Sum	2965.00	2009.46
	Mean	29.6500	20.0946
	Std. Deviation	40.32436	28.61418

Table 4.22e: ANOVA Table

			Sum of Squares	df	Mean Square	F	Sig.
WSP * Weekly Sample Collected	Between Groups	(Combined)	1175.526	9	130.614	.074	1.000
	Within Groups		159803.846	90	1775.598		
	Total		160979.371	99			
CWS * Weekly Sample Collected	Between Groups	(Combined)	1128.780	9	125.420	.141	.998
	Within Groups		79929.578	90	888.106		
	Total		81058.357	99			

Table 4.22f: Correlations

		INLET	WSP	CWS
INLET	Pearson Correlation	1	.974**	.896**
	Sig. (2-tailed)		.000	.000
	N	100	100	100
WSP	Pearson Correlation	.974**	1	.957**
	Sig. (2-tailed)	.000		.000
	N	100	100	100
CWS	Pearson Correlation	.896**	.957**	1
	Sig. (2-tailed)	.000	.000	
	N	100	100	100
**. Correlation is significant at the 0.01 level (2-tailed).				

The relationship between waste stabilization pond and constructed wetland effluents are highly and positively correlated. There was statistically significant difference at the $p < 0.01$ level in removal efficiencies of physico-chemical pollutants for WSP and CW $F (9, 181.348) = 21.632$, $p=0.01$. Despite reaching statistical significant, the actual difference in mean values between WSP and CW was high (i.e. Mean for WSP and CW = 29.6500 and

20.0946 respectively). This study observed that the constructed wetland significantly removed physico-chemical pollutants more than waste stabilization pond.

4.22 Modelling of Constructed Wetland Results

4.22.1 Lead

The calculated concentration logarithm after seven days residence time for the period of ten weeks for Lead is given in Table 4.23a. Relationship between the observed concentration logarithm and the residence time after 7 days for 10 weeks period is shown in Figure 4.39. Figure 4.39 shows that the relationship is strong (R^2= 63.2) and linear, with removal rate increasing as the resident time is increased. The model summary of analysis using SPSS program is shown in Table 4.23b**.** Table 4.23b shows that the relationship between observed concentration logarithm and resident time for Lead is high (R = 0.79) and the goodness of fit is (R^2 = 63.2%). The coefficients of dependent variable (concentration logarithm) are shown in Table 4.23c. The Microsoft Office Software EXCEL XP and SPSS program can be recommended for analysis of wetland performance.

Table 4.23a: Calculated concentration logarithm of Lead (Pb) for seven days residence time for the period of ten weeks

Hydraulic resident time (Weeks)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Ln{(C_o-2.155)/ (C_i-2.155)}	-1.142	-1.017	-1.247	-0.981	-1.101	-1.438	-2.201	-2.201	-2.129	-2.094

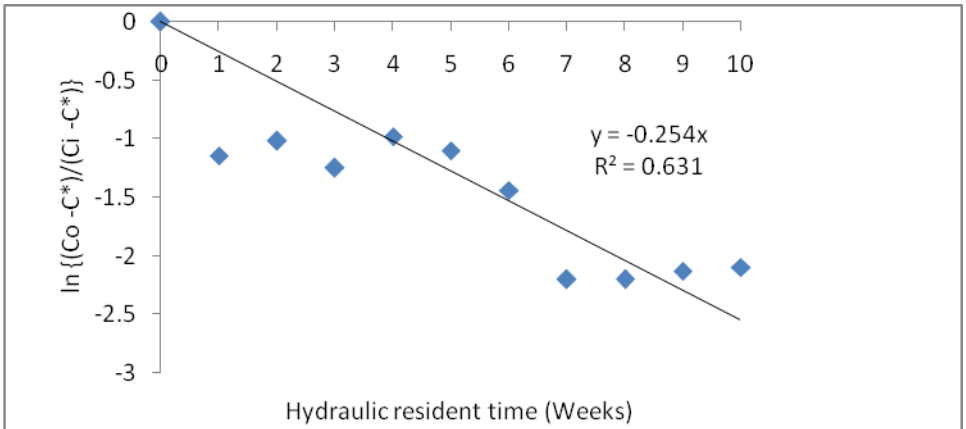


Fig. 4.39: Regression analysis of observed concentration logarithm on hydraulic resident time for Lead (Pb)

ln{(Co-C*)/(Ci-C*)}= Calculated concentration logarithm

Table 4.23b: Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics		
					R Square Change	F Change	df1
1	.889[a]	.790	.767	.333093794741	.790	33.854	1

Table 4.23c: Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-.490	.188		-2.606	.028
	Week	-.185	.032	-.889	-5.818	.000

a. Dependent Variable: ln{(Co-C*)/(Ci-C*)}

4.22.2 Zinc

The first order dynamic model was used to describe the reduction of pollutants. The calculated concentration logarithm for Zinc after seven days residence time for the period of ten weeks was calculated and shown in Table 4.24a

Table 4.24a: Calculated concentration logarithm of Zinc (Zn) for seven days residence time for the period of ten weeks

Hydraulic resident time (Weeks)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
$Ln\{(C_o-2.155)/(C_i-2.155)\}$	-0.51	-0.478	-0.578	-0.635	-0.719	-0.806	-1.049	-1.332	-0.211	-0.341

Solution of the equation using a sub-program of Microsoft Office Software EXCEL XP gives a linear relationship in the concentration logarithm with the residence time as shown in Fig. 4.40. The relationship is strong (R^2= 80.7%) and linear, with removal rate increasing as the resident time increases. The model summary of analysis performed using SPSS program is shown in Table 4.24b**.** The relationship between Zinc removal and resident time is high (R = 0.924) and the goodness of fit is high too, (R^2 = 86.6%). The coefficients of dependent variable (concentration logarithm) are shown in Table 4.24c. The 5.8% variation in the R^2 between the programs indicates that the goodness of fit of both programs is closely related and any of the models can be used to determine wetland performance

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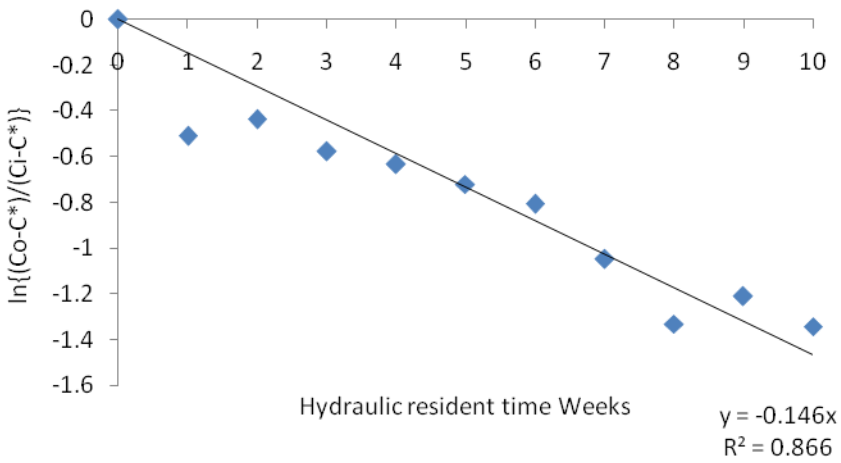


Fig. 4.40: Zinc (Zn) Concentration in Inlet and Outlet Wastewater of Constructed Wetland and Waste Stabilization Pond

ln{(Co-C*)/(Ci-C*)}= Calculated concentration logarithm

Table 4.24b: Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics		
					R Square Change	F Change	df1
1	.961[a]	.924	.915	.121374344923	.924	109.221	1

Table 4.24c: Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-.179	.068		-2.611	.028
	Week	-.121	.012	-.961	-10.451	.000

a. Dependent Variable: ln{(Co-C*)/(Ci-C*)}

4.21.3 Manganese

The calculated concentration logarithm of the Manganese after seven days residence time for the period of ten weeks is shown in Table 4.25a.

Table 4.25a: Calculated concentration logarithm of Manganese (Mn) for seven days residence time for the period of ten weeks

Hydraulic resident time (Weeks)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Ln{(C_o-2.155)/ (C_i-2.155)}	-0.723	-0.779	-1.083	-1.153	-1.21	-1.091	-1.291	-1.723	-5.361	-6.465

Solution of the equation using a sub-program of Microsoft Office Software EXCEL XP gives a linear relationship in the concentration logarithm with the residence time as shown in Fig. 4.41. The relationship is strong (R^2= 89.8%) and linear, with removal rate increasing as the resident time increases. The model summary of analysis performed using SPSS program is shown in Table 4.25b**.** The relationship between Manganese removal and resident time is very high (R = 0.635) and the goodness of fit is equally high (R^2 = 61.19%). The coefficients of dependent variable (concentration logarithm) are shown in Table 4.25c. A negligible variation in the R^2 indicates that the goodness of fit for both programs is closely related and thus, the variation in R^2 can be ignored as both models can achieve the similar output.

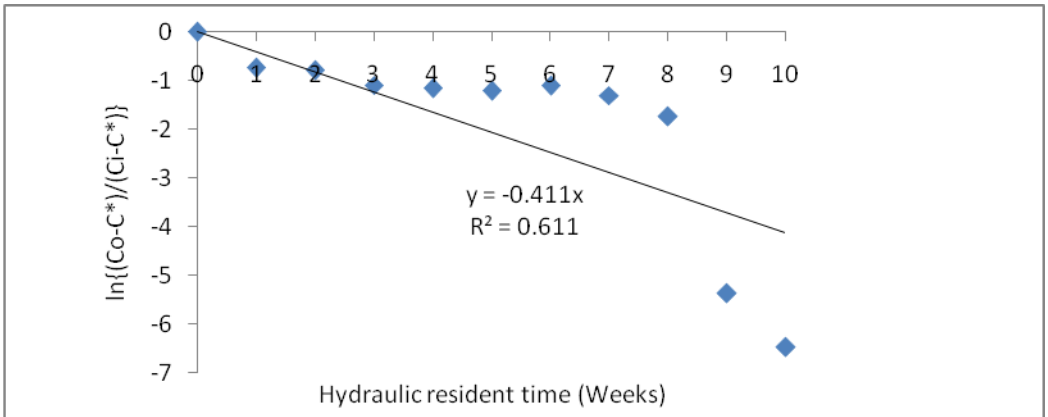


Fig. 4.41: Regression analysis of observed concentration logarithm on hydraulic resident time for Manganese (Mn)

ln{(Co-C*)/(Ci-C*)}= Calculated concentration logarithm

Table 4.25b: Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics		
					R Square Change	F Change	df1
1	.797[a]	.635	.595	1.301581154050	.635	15.687	1

Table 4.25c: Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.559	.734		.762	.466
	Week	-.492	.124	-.797	-3.961	.003

a. Dependent Variable: ln{(Co-C*)/(Ci-C*)}

4.22.4 Magnesium

The calculated concentration logarithm of the Magnesium after seven days residence time for the period of ten weeks is shown in Table 4.26a.

Table 4.26a: Calculated concentration logarithm of Magnesium (Mg) for seven days residence time for the period of ten weeks

Hydraulic resident time (Weeks)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
$Ln\{(C_o-2.155)/(C_i-2.155)\}$	-0.805	-0.787	-0.884	-0.996	-1.109	-1.17	-1.423	-1.388	-1.692	-1.72

Solution of the equation using a sub-program of Microsoft Office Software EXCEL XP gives a linear relationship in the concentration logarithm with the residence time as shown in Fig. 4.42. The model summary of analysis performed using SPSS program is shown in Table 4.26b**.** The relationship between Magnesium removal and resident time is high (R = 0.883) and the goodness of fit is high (R^2 = 67.5%). The coefficients of dependent variable (concentration logarithm) are shown in Table 4.26c. A slight variation in the R^2 from the goodness of fit for both programs can be observed. This variation in R^2 can be considered negligible as both models can be used for wetland performance.

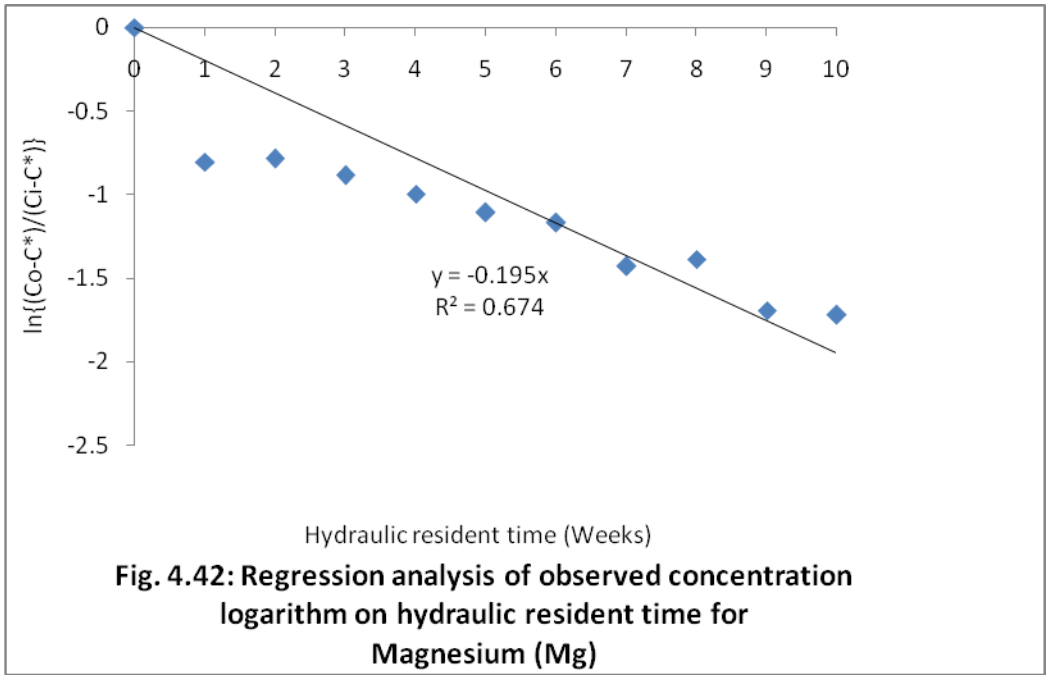


Fig. 4.42: Regression analysis of observed concentration logarithm on hydraulic resident time for Magnesium (Mg)

ln{(Co-C*)/(Ci-C*)}= Calculated concentration logarithm

Table 4.26b: Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics		
					R Square Change	F Change	df1
1	.940[a]	.883	.870	.175727754880	.883	68.111	1

Table 4.26c: Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-.398	.099		-4.012	.003
	Week	-.138	.017	-.940	-8.253	.000

a. Dependent Variable: ln{(Co-C*)/(Ci-C*)}

4.22.5 Silver (Ag)

The calculated concentration logarithm of the Magnesium after seven days residence time for the period of ten weeks is shown in Table 4.27a.

Table 4.27a: Calculated concentration logarithm of Silver (Ag) for seven days residence time for the period of ten week

Hydraulic resident time (Weeks)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
$Ln\{(C_o-2.155)/(C_i-2.155)\}$	-0.585	-0.655	-0.757	-0.904	-1.022	-0.914	-0.974	-0.93	-1.11	-1.23

Solution of the equation using a sub-program of Microsoft Office Software EXCEL XP gives a linear relationship in the concentration logarithm with the residence time as shown in Fig. 4.43. This relationship is low (R^2= 30.7%) and linear, with removal rate increasing as the resident time increases. The data result obtained is an indicative that first order kinetic equation of the heavy metal silver (Ag) cannot be used as a predictive model for construction wetland at 10 weeks operational period. The model summary of analysis performed using SPSS program is shown in Table 4.27b**.** The relationship between silver removal and resident time is (R = 0.74). The coefficients of dependent variable (concentration logarithm) are shown in Table 4.27c. The observed R^2 from the goodness of fit for both programs shows a variation.

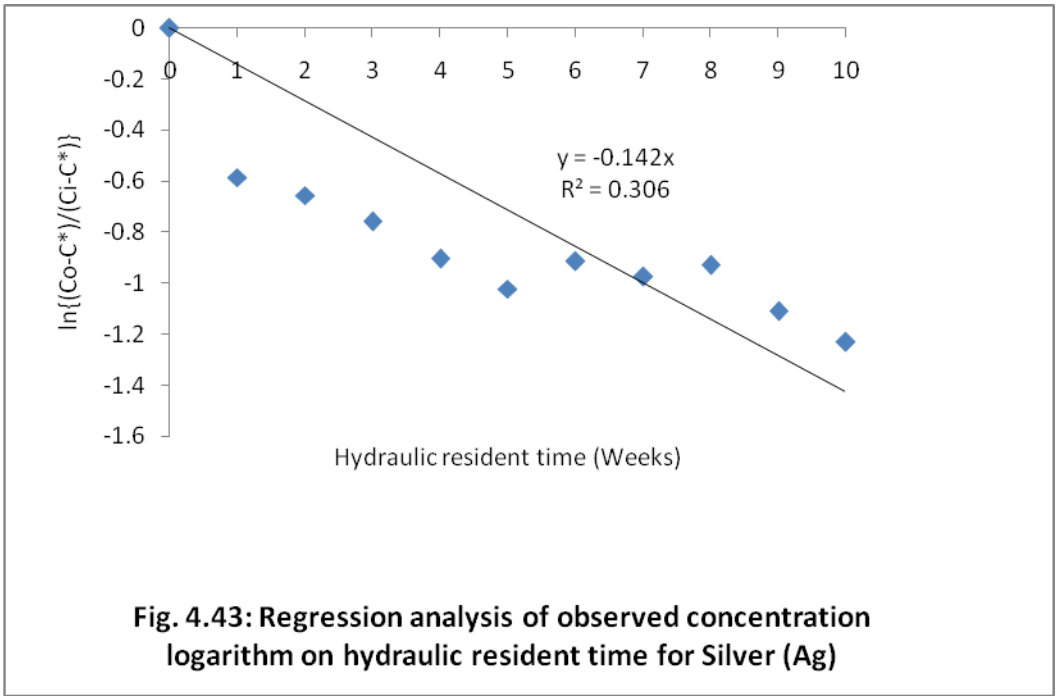


Fig. 4.43: Regression analysis of observed concentration logarithm on hydraulic resident time for Silver (Ag)

ln{(Co-C*)/(Ci-C*)}= Calculated concentration logarithm

Table 4.27b: Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics		
					R Square Change	F Change	df1
1	.864[a]	.747	.718	.176264822669	.747	26.513	1

Table 4.27c: Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-.393	.099		-3.951	.003
	Week	-.087	.017	-.864	-5.149	.001

a. Dependent Variable: ln{(Co-C*)/(Ci-C*)}

4.22.6 Cobalt (Co)

The calculated concentration logarithm of the Cobalt after seven days residence time for the period of ten weeks is shown in Table 4.28a.

Table 4.28a: Calculated concentration logarithm of Cobalt (Co) for seven days residence time for the period of ten weeks

Hydraulic resident time (Weeks)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Ln{(C_o-2.155)/ (C_i-2.155)}	0	0	0	-0.325	-0.424	-0.424	-0.502	-0.572	-1.159	-1.72

Solution of the equation using a sub-program of Microsoft Office Software EXCEL XP gives a linear relationship in the concentration logarithm with the residence time as shown in Fig. 4.44. The relationship is strong (R^2= 67.9%) and linear, with removal rate increasing as the resident time increases. The model summary of analysis performed using SPSS program is shown in Table 4.28b**.** The relationship between Cobalt removal and resident time is very high (R = 0.725) and the goodness of fit is (R^2 = 67.9%). The coefficients of dependent variable (concentration logarithm) are shown in Table 4.28c. The observed good of fit values (R^2) using the Microsoft Office Software EXCEL XP and SPSS program are strong and therefore, any of the two programs can be utilized for modeling constructed wetland.

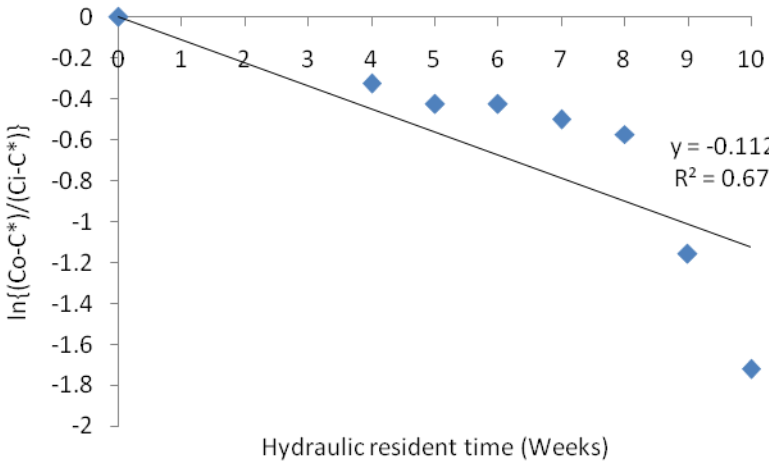


Fig. 4.44: Regression analysis of observed concentration logarithm on hydraulic resident time for Cobalt (Co)

ln{(Co-C*)/(Ci-C*)}= Calculated concentration logarithm

Table 4.28b: Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics		
					R Square Change	F Change	df1
1	.851[a]	.725	.679	.307459350660	.725	15.795	1

Table 4.28c: Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.248	.249		.998	.357
	Week	-.145	.037	-.851	-3.974	.007

a. Dependent Variable: ln{(Co-C*)/(Ci-C*)}

4.22.7 Chromium (Cr)

The calculated concentration logarithm of the Chromium after seven days residence time for the period of ten weeks is shown in Table 4.29a.

Table 4.29a: Calculated concentration logarithm of Chromium (Cr) for seven days residence time for the period of ten weeks

Hydraulic resident time (Weeks)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
$Ln\{(C_o-2.155)/(C_i-2.155)\}$	-0.765	-0.802	-0.855	-0.924	-1.112	-1.165	-1.243	-1.452	-1.806	-2.175

Solution of the equation using a sub-program of Microsoft Office Software EXCEL XP gives a linear relationship in the concentration logarithm with the residence time as shown in Fig. 4.45. This relationship is strong (R^2= 80.8%) and linear, with removal rate increasing as the resident time increases. The model summary of analysis performed using SPSS program is shown in Table 4.29b**.** Table 4.27b shows that the relationship between Chromium removal and resident time is very high (R = 0.893) and the goodness of fit is equally high (R^2 = 80.8%). The coefficients of dependent variable (concentration logarithm) are shown in Table 4.29c. A variation in the R^2 indicates that the goodness of fit for both programs is closely related and thus, the variation in R^2 (8.5%) can be ignored as both models can achieve the same output.

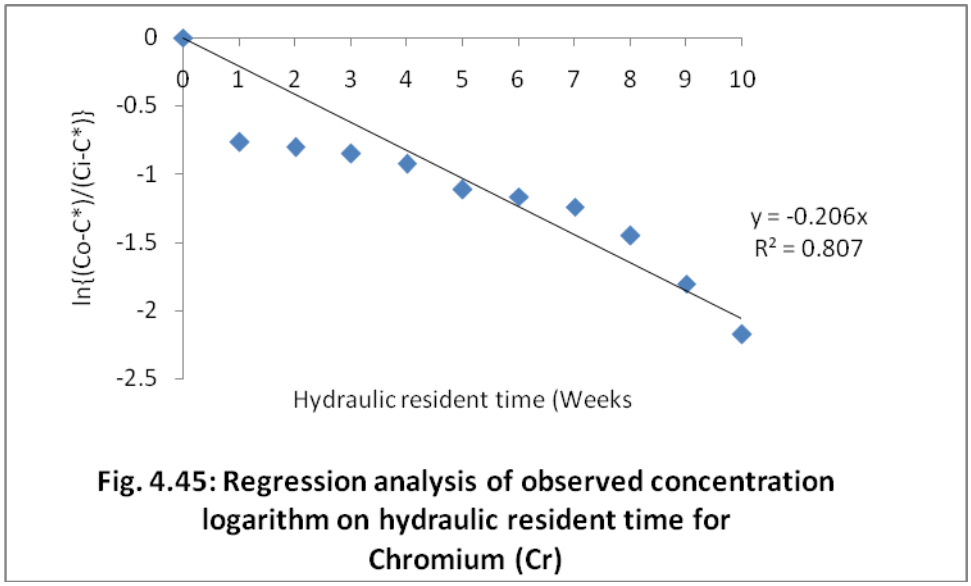


Fig. 4.45: Regression analysis of observed concentration logarithm on hydraulic resident time for Chromium (Cr)

ln{(Co-C*)/(Ci-C*)}= Calculated concentration logarithm

Table 4.29b: Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics		
					R Square Change	F Change	df1
1	.945[a]	.893	.881	.198187416537	.893	75.052	1

Table 4.29c: Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-.299	.112		-2.678	.025
	Week	-.164	.019	-.945	-8.663	.000

a. Dependent Variable: ln{(Co-C*)/(Ci-C*)}

4.22.8 Cadmium (Cd)

The calculated concentration logarithm of the Cadmium after seven days residence time for the period of ten weeks is shown in Table 4.30a.

Table 4.30a: Calculated concentration logarithm of Cadmium (Cd) for seven days residence time for the period of ten weeks

Hydraulic resident time (Weeks)	1	2	3	4	5	6	7	8	9	10
$Ln\{(C_o-2.155)/(C_i-2.155)\}$	-2.18	-2.31	-2.261	-2.381	-2.424	-2.35	-2.435	-2.493	-2.592	-2.827

Solution of the equation using a sub-program of Microsoft Office Software EXCEL XP gives a linear relationship in the concentration logarithm with the residence time as shown in Fig. 4.46. This relationship is strong (R^2= 72%) and linear, with removal rate increasing as the resident time increases. The model summary of analysis performed using SPSS program is shown in Table 4.30b**.** Table 4.28b shows that the relationship between Cadmium removal and resident time is (R = 0.446) and the goodness of fit is equally very high (R^2 = 72%). The coefficients of dependent variable (concentration logarithm) are shown in Table 4.30c.

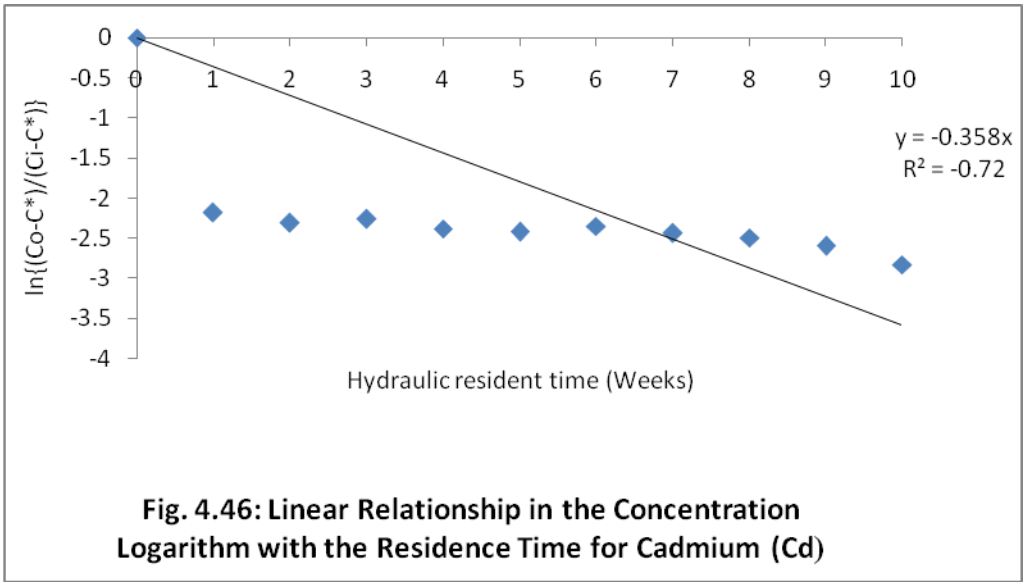


Fig. 4.46: Linear Relationship in the Concentration Logarithm with the Residence Time for Cadmium (Cd)

ln{(Co-C*)/(Ci-C*)}= Calculated concentration logarithm

Table 4.30b: Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics		
					R Square Change	F Change	df1
1	.668[a]	.446	.385	.589672144847	.446	7.251	1

Table 4.30c: Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-1.448	.333		-4.353	.002
	Week	-.151	.056	-.668	-2.693	.025

a. Dependent Variable: ln{(Co-C*)/(Ci-C*)}

4.22.9 Iron (Fe)

The calculated concentration logarithm of the Iron after seven days residence time for the period of ten weeks is shown in Table 4.31a.

Table 4.31a: Calculated concentration logarithm of Iron (Fe) for seven days residence time for the period of ten weeks

Hydraulic resident time (Weeks)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
$Ln\{(C_o-2.155)/(C_i-2.155)\}$	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023

Solution of the equation using a sub-program of Microsoft Office Software EXCEL XP gives a linear relationship in the concentration logarithm with the residence time as shown in Fig. 4.47. This relationship is low (R^2= 21.34%) and model summary of analysis performed using SPSS program is shown in Table 4.31b**.** Table 4.29b shows that the relationship between iron removal and resident time is very low (R = 0.288) and the goodness of fit is equally very low (R^2 = 21.34%). The coefficients of dependent Variable (concentration logarithm) are shown in Table 4.31c.

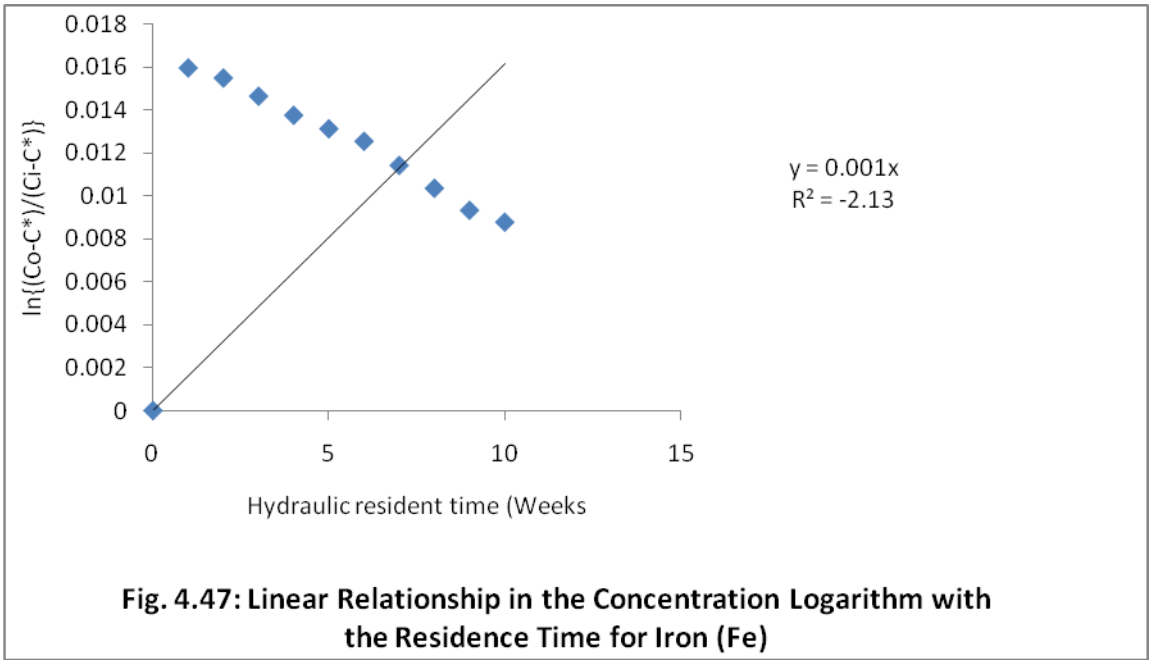


Fig. 4.47: Linear Relationship in the Concentration Logarithm with the Residence Time for Iron (Fe)

ln{(Co-C*)/(Ci-C*)}= Calculated concentration logarithm

Table 4.31b: Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics		
					R Square Change	F Change	df1
1	.530[a]	.280	.200	.006183198276	.280	3.508	1

Table 4.31c: Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.015	.003		4.391	.002
	Week	.001	.001	.530	1.873	.094

a. Dependent Variable: ln{(Co-C*)/(Ci-C*)}

4.22.10 Copper (Cu)

The calculated concentration logarithm of the Copper after seven days residence time for the period of ten weeks is shown in Table 4.32a.

Table 4.32a: Calculated concentration logarithm of Copper (Cu) for seven days residence time for the period of ten weeks

Hydraulic resident time (Weeks)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
$Ln\{(C_o-2.155)/(C_i-2.155)\}$	-0.831	-0.881	-0.5	-1.086	-1.548	-1.846	-2.119	-2.485	-1.373	-2.511

Solution of the equation using a sub-program of Microsoft Office Software EXCEL XP gives a linear relationship in the concentration logarithm with the residence time as shown in Fig. 4.48. This relationship is strong (R^2= 71.63%) and linear, with removal rates increasing as the resident time increases. The model summary of analysis performed using SPSS program is shown in Table 4.32b**.** Table 4.32b shows that the relationship between Copper removal and resident time is very high (R = 0.762) and the goodness of fit is equally high (R^2 = 71.63%). The coefficients of dependent variable (concentration logarithm) are shown in Table 4.32c. It can be observed that the good of fit using the Microsoft Office Software EXCEL XP and SPSS program are of close ranking and thus any of the two programs is recommended.

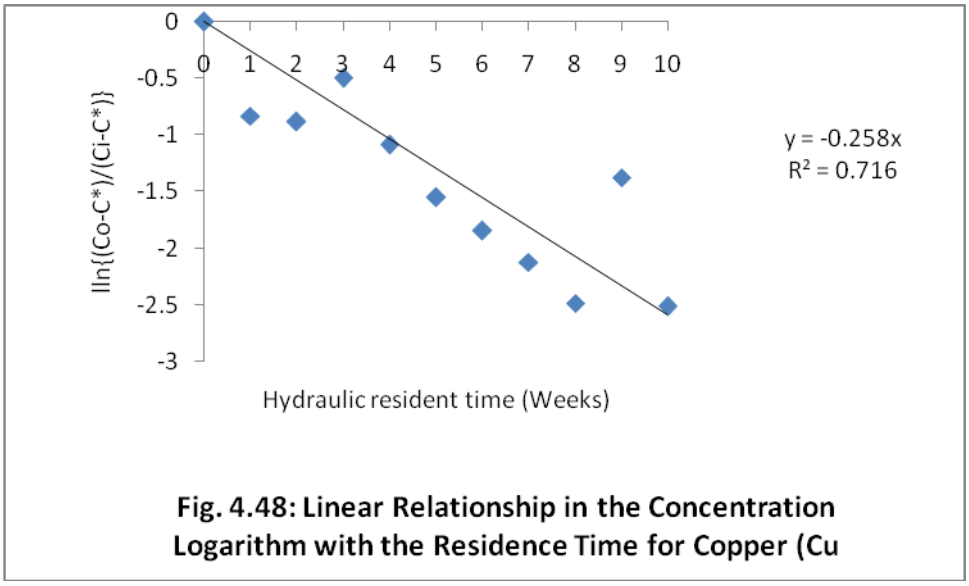


Fig. 4.48: Linear Relationship in the Concentration Logarithm with the Residence Time for Copper (Cu

ln{(Co-C*)/(Ci-C*)}= Calculated concentration logarithm

Table 4.32b: Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics		
					R Square Change	F Change	df1
1	.873[a]	.762	.736	.417870681789	.762	28.829	1

Table 4.32c: Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-.310	.236		-1.317	.221
	Week	-.214	.040	-.873	-5.369	.000

a. Dependent Variable: ln{(Co-C*)/(Ci-C*)}

4.23 Constructed wetland costs

The estimated costs of the constructed wetland system are presented in Table 4.33.

Table 4.33: Constructed Wetland Costs

S/N	Description	Unit	Quantity	Rate (N)	Amount (N)
	A. Construction cost				
1	Site clearing	m^2	52	150.00	7,800.00
2	Excavation of constructed wetland to depth of g 450mm from ground surface	m^3	38	600.00	22,800.00
3	Disposal of excavated material	m^3	38	350.00	13,300.00
4	Supply and laying of 0.50 mm thick nylon geomembrane on the walls of the excavation	m^2	78	150.00	11,700.00
5	Supply and installation of 3500mm X 1000mm wire mesh galvanised gabion baskets	M	9	15,000.00	135,000.00
6	Supply and filing the gabion baskets with stone boulders average size of 100mm	m^3	7	5,500.00	38,500.00
7	Supply and placing of 20mm coarse gravel on spread nylon geomembrane	m^3	8	4,500.00	36,000.00
8	Supply and placing of sand on the 20mm coarse gravel	m^3	8	2,400.00	19,200.00
9	Supply and uniform spreading of 0.50mm thick local vegetable soil on placed sand	m^2	36	1,250.00	45,000.00
10	Supply and planting aquatic plants on local vegetable soil	m^2	36	500.00	18,000.00
11	Supply and installation of l 75mm flexible delivery hose	M	55	450.00	24,750.00
12	Supply and installation of l 2HP gasoline pump	No	1	25,000.00	25,000.00
13	Supply and installation 3,000 litres plastic tank	No	1	45,000.00	45,000.00
14	Supply and laying 50mm PVC pipe	M	25	450.00	11,250.00
15	Supply and laying of 50mm perforated PVC pipe	M	3	860.00	2,580.00
16	Supply and laying of 20mm uPVC pipe	M	5	150	750.00
17	50mm gate valves	Nos	3	3000	9,000.00
18	50mm X 50mm X 50mm Tee	No	1	850	850.00
19	50mm PVC plug	Nos	2	500	1,000.00
20	20mm gate valves	No	1	550	550.00
21	Excavate and back filing of the trench for the 50mm PVC pipe	M	25	500	12,500.00
22	Excavate and backfilling of trench for the 20mm PVC pipe	M	5	400	2,000.00
	Sub- Total				**482,530.00**
	B. Operation and maintenance cost				
23	Hiring of Water pump	week	27	1,000	27,000.00
24	Fuelling of water pump	litres	378	140	52,920.00
25	Weeding	Nos	7	2,000	14,000.00
	Sub- Total				**93,920.00**
	Grand Total				**576,450.00**

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In this study, the efficiencies of heavy metal removal from the wastewater of Ahmadu Bello University, Zaria by horizontal flow sub-surface constructed wetland were evaluated and compared with ABU waste stabilization pond removals for a period of ten (10) weeks at seven (7) days hydraulic retention time. The conclusions are as follows:

1. The constructed wetland was able to remove considerable amounts of the heavy metals in the wastewater of ABU. These heavy metals otherwise would have been discharged into Kubani River at the downstream of the University dam. The maximum removal efficiencies by the constructed wetland for Pb, Zn, Mn, Mg, Ag, Co, Cr, Cd, Fe and Cu were 86.8%, 71.83%, 97.69%, 80%, 68.81%, 90%, 86.51%, 89.34%, 68.18% and 90% respectively. On the other hand, the maximum removal efficiency by the ABU waste stabilization pond for Pb, Zn, Mn, Mg, Ag, Co, Cr, Cd, Fe and Cu were 10.53%, 7.64%, 6.91%, 8.07%, 8.05%, 5.8%, 4.12%, 4.61%, 11.23% and 9.91% respectively.
2. During the same period, the constructed wetland removed TSS, FC, BOD, COD, PO_4-, NO_3- and NH_4- by 89.2%, 94.3%, 93%, 80.5%, 67.5%, 80.5% and 32.92% respectively compared with the ABU waste stabilization pond by 78.6%, 81.1%, 78.3%, 69.8%, 38.12%, 72.6% and 17.02% respectively.
3. The DO concentration increased from 2.70 – 4.70mg/L during ten (10) weeks of study. This indicates that constructed wetlands may be eco-friendly in terms of dissolved oxygen content.

4. The average pH and temperature of effluent from constructed wetland were 7.16 and 28.03 ^{0}C respectively and they fall within the permissible discharge limits of Food and Agricultural Organisation (FAO) and World Health Organisation (WHO) Standards.

5. Very low or zero energy input was required by the constructed wetland just like waste stabilization pond , making its operation and maintenance costs much lower compared to conventional treatment systems.

6. The results of physicochemical and biological measurements of the treated effluent by the constructed wetland fall within the permissible discharge limits of Food and Agricultural Organisation (FAO) and World Health Organisation (WHO) effluent standards, making the treated effluent amenable for wastewater reuse in agriculture.

7. The Microsoft Office Software EXCEL XP and SPSS programs were used to derive reliable statistical efficiency models which are closely similar in goodness of fit, and the statistical analysis revealed satisfactory agreement between model predictions and measurements proving the adequacy of the models.

8. Statistically, relationship between waste stabilization pond and constructed wetland effluents are highly and positively correlated. There was statistically significant difference at $p < 0.01$ level in removal efficiencies of heavy metals for WSP and CW $F(9, 181.348) = 21.632$, $p=0.01$. In addition to reaching statistical significant, the actual difference in mean values between WSP and CW was significant too (i.e. Mean for WSP and CW = 1.667420 and 0.745740 respectively). There was also statistically significant difference at the $p < 0.01$ level in removal efficiencies of physico-chemical pollutants for WSP and CW $F(9, 181.348) = 21.632$, $p=0.01$. The actual difference in mean values between WSP and CW was also significant

(i.e. Mean for WSP and CW = 29.6500 and 20.0946 respectively). This study observed that the constructed wetland significantly removed heavy metals and physico-chemical pollutants more than waste stabilization pond.

5.2 Recommendations

On the basis of this study and the accompanying analysis, the following recommendations are hereby made:

1. For better quality of effluent wastewater discharge from ABU, the waste stabilization pond effluent could be improved by incorporating a constructed wetland, before discharging it into the Kubani River.
2. There is need to carryout studies on the accumulation of heavy metals in crops irrigated with the wastewater effluents from ABU waste stabilization ponds.
3. Microsoft Office Software EXCEL XP and SPSS programs are recommended for wetland modeling as they help to understand the physicochemical and biological processes taking place in constructed wetlands.
4. The results of the study of pilot scale constructed wetland treatment of wastewater in Ahmadu Bello University, Zaria can serve as a base for further researches on phyto-remediation and bio-remediation.

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APPENDICES

APPENDIX I

Water Quality for Irrigation: World Health Organization Standards (1994)

S/N	Parameters	Excellent Quality	Good Quality	Unsuitable Quality
1	PH	< 6.0	6.0-8.5	> 8.5
2	E.C. (mmhos/cm)	< 0.78	0.780-1.60	> 1.6
3	Sulphate (mg/l)	< 240	240-500	> 500
4	Nitrate (mg/l)	< 5.0	5.0-50	> 50
5	Bicarbonate (mg/l)	< 80	80-500	> 500
6	Carbonate (mg/l)	< 50	50-200	> 200
7	Magnesium (mg/l)	< 30	30-150	> 150
8	Chloride (mg/l)	< 200	200-600	> 600
9	Calcium (mg/l)	< 75	75.0-200.0	> 200
10	Baron (mg/l)	< 1.0	1.0-2.00	> 2.00
11	Sodium (mg/l)	< 50	50-200	> 200
12	SAR (mmol/l)	< 10	10-15.0	> 15.00
13	TDS (mg/l)	< 500	500-1000	> 1000
14	RSC (mg/l)	< 1.0	1.5-2.50	> 2.50
15	Phosphate (mg/l)	< -----	0-2.00	> 2.0
16	Manganese (mg/l)	< 0.5	0.50-1.50	> 1.50
17	Iron (mg/l)	< 0.20	0.20-1.50	> 1.50

APPENDIX II

Water Quality for Irrigation: Food and Agriculture Organization Standards (1985)

S/N	Parameters	Excellent Quality	Good Quality	Unsuitable Quality
1	PH	< 6.0	6.0-8.4	> 8.4
2	E.C. (mmhos/cm)	< 0.7	0.7-3.0	> 3.0
3	Sulphate (mg/l)	< 200	0-200	> 200
4	Nitrate (mg/l)	< 5.0	5.0-30.0	> 30.0
5	Bicarbonate (mg/l)	< 90.0	90.0-520.0	> 520.0
6	Carbonate (mg/l)	< 60	60-200	> 200
7	Magnesium (mg/l)	< 20	20-120	> 120
8	Chloride (mg/l)	< 142	142-335	> 335
9	Calcium (mg/l)	< 150	150-400	> 400
10	Baron (mg/l)	< 0.7	0.7-3.00	> 3.00
11	Sodium (mg/l)	< 100	100-300	> 300
12	SAR (mmol/l)	< 8.0	8.0-20.0	> 20.00
13	TDS (mg/l)	< 450	450-2000	> 2000
14	RSC (mg/l)	< 2.0	2.0-4.9	> 4.90
15	Phosphate (mg/l)	< -----	0-2.0	> 2.0
16	Manganese (mg/l)	< 1.0	1.0-1.50	> 1.50
17	Iron (mg/l)	< 0.20	0.20-1.50	> 1.50