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Performance of horizontal subsurface flow constructed wetland integrated with floating wetland and anaerobic baffled reactor in treating seed production wastewater

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PERFORMANCE OF HORIZONTAL SUBSURFACE FLOW CONSTRUCTED WETLAND INTEGRATED WITH FLOATING WETLAND AND ANAEROBIC BAFFLED REACTOR IN TREATING SEED PRODUCTION WASTEWATER

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A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree Master's in Environmental Science and Engineering of the Nelson Mandela African Institution of Science and Technology

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ABSTRACT

Discharge of untreated or partially treated industrial wastewater is the major contributor to aquatic environmental pollution. Seed producing industrial wastewater is composed of high organic matter, nutrient, and suspended solids. Discharging inadequately treated seed production wastewater can cause severe environmental pollution because of high nutrients and organic matter in the wastewater. The performance of integrated wastewater treatment system composed of anaerobic baffled reactor (ABR), horizontal subsurface flow constructed wetland (HSSFCW), and floating constructed wetland (FCW) for removal of pollutants from seed production industrial wastewater was studied. In HSSFCW, *Cyperus alternifolius* were planted with four rhizomes in each square meter, and the FCW had four floating mats made from polyethylene foam planted with *Vetiver* grass. The wetlands were continuously fed from ABR receiving $25\,\mathrm{m}^3$/day wastewater from wastewater reservoir. The raw wastewater average organic loading rate was 0.208 kg COD/day. Wastewater samples from the inlet and outlet of each treatment unit were collected twice a week for three months. The performance of the system in removal of biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), turbidity, nitrate, phosphate, and ammonium were studied. The results showed that the system achieved an average removal efficiency of 95.52%, 94.57%, 86.23%, 76.56%, 82.35%, 76%, and 32.91% for BOD_5, COD, TSS, turbidity, nitrate, phosphate, and ammonium respectively. Based on the results obtained the integrated system composed of ABR, HSSFCW, and FCW is a promising low-cost technology for treating wastewater from seed producing industries, and the treated wastewater can be used for irrigation.

DECLARATION

I **Elizabeth Serekebirhan Kiflay** do hereby declare to the Senate of Nelson Mandela African Institution of Science and Technology that this dissertation is my original work and it has neither been submitted nor being concurrently submitted for degree award in any other institution.

Elizabeth Serekebirhan Kiflay ________________ ____________________

Name and signature of the candidate **Date**

The above declaration is confirmed

Prof. Karoli Nicholas Njau ________________ ____________________

Name and signature of supervisor (1) **Date**

Dr. Juma Rajabu Selemani ________________ ____________________

Name and signature of supervisor (2) **Date**

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CERTIFICATION

The undersigned certify that they have read and found that the dissertation conforms to the standard and format acceptable for submission. Therefore, do hereby recommend for acceptance of dissertation entitled "**Performance of horizontal subsurface flow constructed wetland integrated with floating wetland and anaerobic baffled reactor in treating seed production wastewater"**, in fulfilment of the requirements for the degree of Master's in Environmental Science and Engineering at Nelson Mandela African Institution of Science and Technology.

Prof. Karoli Nicholas Njau ____________________ _________________________

Name and signature of supervisor (1) Date

Dr. Juma Rajabu Selemani _____________________ _______________________

Name and signature of supervisor (2) Date

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DEDICATION

This work is dedicated to my parents: my mom Almaz Kifle, my dad Serekebirhan Kiflay, my boyfriend Michael Petros and the rest of the family. Their prayer, support, encouragement, love, and care gave me the strength and power in my life.

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LIST OF ABRIVATIONS AND SYMBOLS

ABR	Anaerobic Baffled Reactor
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
CWs	Constructed Wetlands
EC	Electric Conductivity
FCWs	Floating Constructed Wetlands
FTU	Formazin Turbidity Unit
FWSCWs	Free Water Surface Constructed Wetlands
HRT	Hydraulic Retention Time
HSSFCWs	Horizontal Subsurface Flow Constructed Wetlands
OLR	Organic Loading Rate
SS	Suspended Solids
SRT	Solid Retention Time
TBS	Tanzania Bureaus of Standard
TDS	Total Dissolved Solids
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
UASBR	Up flow Anaerobic Sludge Blanket Reactor
VSSFCW	Vertical Subsurface Flow Constructed wetland
WHO	World Health Organization

CHAPTER ONE

INTRODUCTION

1.1 Background of the problem

Industries contribute greatly to the economic growth of any country however, they are main sources of aquatic pollution (Kadirvelu *et al*., 2001). Seed production industrial wastewater is among strong wastewater composed of high organic matter, nutrients, and other pollutants. Therefore, it is important to treat industrial effluents adequately before discharging into the environment.

Anaerobic digestions are considered as effective method for high-strength wastewater treatment in organic and suspended solids removal (Akunna & Clark, 2000). Besides, anaerobic treatment systems are characterized by less energy consumption and less sludge production, which results in low operational cost. Anaerobic baffled reactor (ABR) is an anoxic wastewater treatment system composed of continuous vertical baffles that allow the wastewater to pass below and on top (Bachmann *et al*., 1985). Several studies proved the effective removal ability of ABR for organics and total suspended solids from industrial wastewater (Movahedyan *et al*., 2007; Ferraz *et al*., 2009; Alighardashi *et al*., 2015). However, the nitrification process is restricted in the system, and the concentration of ammonium increases due to the anoxic environment. Therefore, additional post-treatment is required to reduce the concentration of ammonium, pathogens, residual chemical oxygen demand (COD), residual biological oxygen demand (BOD_5), and residual total suspended solids (TSS).

Constructed wetlands (CWs) are systems which treat wastewater using the process that involves wetland vegetation, soil or substrate, and living organisms (Naja & Volesky, 2011). Constructed wetlands are considered as effective, efficient, and suitable wastewater treatment systems because they require a low cost to construct and they use less energy to operate (Njau & Renalda, 2010). The most common types of CWs are free water surface CWs (FWSCWs) and subsurface flow CWs (SSFCWs); these wetlands can be horizontal- or vertical flow. Horizontal subsurface flow CWs (HSSFCWs) operate in such a way that the wastewater flows below the CW bed from the inlet to the outlet zone. The wastewater takes a long time when it passes through the substrate (gravel) this is due to its longer hydraulic retention time (HRT). The process of pollutant removal includes physical, chemical, and biological processes. Biochemical oxygen demand and COD are removed by biological degradation, sedimentation, filtration, and adsorption. Additionally, exposure to sunlight, adsorption, sedimentation, and filtration remove the pathogens in the wastewater. Nitrogen is removed from the wastewater by the process of plant uptake, denitrification, nitrification, adsorption, and sedimentation. Moreover, phosphorus is removed by sedimentation, filtration, precipitation, adsorption, and plant uptake (small amount). In general, HSSFCW is very effective in BOD_5, COD, and TSS removal (Zhang *et al*., 2009). However, the nitrification process is influenced due to limited oxygen at the CW bed (Cottingham *et al*., 1999; Rossmann *et al*., 2012). Furthermore, phosphorus is not removed much compared to nitrogen (Khanijo, 2002).

Floating CWs (FCWs) are small artificial platforms that enable plants to grow on the surface of the water (Fig. 1). This arrangement allows the development of a unique ecosystem, which enable to remove pollutants. This system treats the wastewater in the aerobic environment (Tanner *et al*., 2011). The nutrients and other toxic elements from wastewater are taken up by plants whereas microorganisms that formed biofilm on the roots of plants and mat surface degrade the organic matter (Shahid *et al*., 2018).

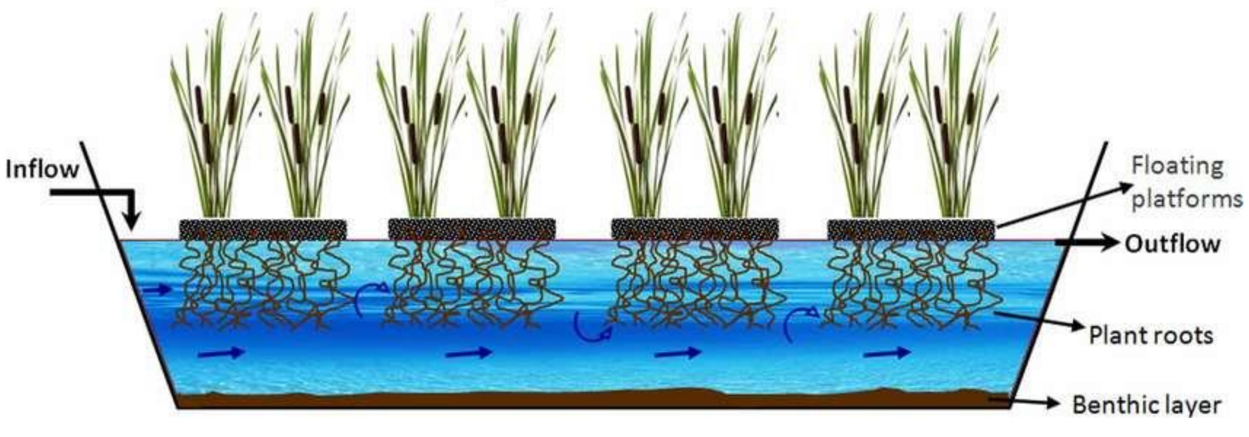


Figure 1: Floating CW (Stefanakis, 2017)

It has been observed that most of the single-stage CWs performed less efficiently in the removal of pollutants from highly loaded wastewater (Sayadi *et al*., 2012). A single-stage CW is not suitable for treating strong industrial wastewater because it might not reach the required wastewater characteristics for discharging into the environment or reuse thus leading to environmental pollution. Researcher de la Varga *et al*. (2016) suggested that for effective treatment of strong industrial wastewater with high load of pollutants different types of CWs must be integrated.

Hybrid CWs are capable of covering the limitation of each single staged CWs. Integrating various types of CWs in a series optimize pollutant reduction via various mechanisms (EL-Khateeb *et al*., 2009; Sayadi *et al*., 2012). Subsurface flow CWs accelerate the denitrification process whereas surface flow CWs accelerate the nitrification process. In both cases, either nitrification or denitrification is limited due to the anaerobic/aerobic conditions of the system. Combining subsurface flow CW and floating CW as a final treatment system expected to reduces nitrogen component from wastewater (Saeed *et al*., 2014).

Hybrid CWs have been studied for different wastewater treatments (El- Khateeb *et al.*, 2009; Saeed *et al*., 2014; Singh *et al*., 2009; Xiong *et al*., 2011; Ye *et al*., 2012). However, studies on integrating SSFCW with FCW for pollutant removal from wastewater are limited. Furthermore, there has been no study or no published data on the application of combined SSFCW and FCW for treating wastewater from the seed production industry. Therefore, this study aimed to combine two CWs namely HSSFCW and FCW with ABR in treating industrial wastewater from seed producing-industries for effective removal of pollutants.

1.2 Statement of the problem

Industries are major polluters of the environment (Hagberg, 2007). In Africa, most industries discharge inadequately treated wastewater into the environment. Environmental pollution is expanding and waste stabilization ponds are the most used technologies for wastewater treatment (Wang *et al*., 2014). However, due to the high load of pollutants in industrial wastewater and the limited capability of stabilization ponds, the concentration of pollutants at the outlet of the system does not meet the required standard. Eutrophication can occur in water bodies exposed to inadequately treated industrial wastewater having excess loads of nitrogen and phosphorus (Bu & Xu, 2013). Moreover, because of high organic matter in the wastewater oxygen depletion, bad odor and fish kills can occur in aquatic environment (Assefa *et al*., 2019). Integrating technologies including anaerobic baffled reactors with non-conventional technologies such as CWs are considered capable of treating a high load of pollutants from industrial wastewater (de la Varga *et al.*, 2016).

1.3 Research objectives

1.3.1 Main objective

The main objective of this study was to evaluate the performance of horizontal subsurface flow constructed wetland integrated with floating constructed wetland and anaerobic baffled reactor in treating seed production industrial wastewater.

1.3.2 Specific objectives

(i) To evaluate the performance of each treatment stage.
(ii) To evaluate the overall performance of the integrated system and to compare the concentration of the pollutants from the wastewater at the outlet of the integrated system with the standard.

1.4 Research questions

(i) How does each stage contribute to the treatment chain of the integrated system?
(ii) What is the overall performance of the integrated treatment system?

1.5 Significance of the research

Water is a scarce and limited resource. However, human activities are still diminishing this scarce resource. Wastewater treatment is a tool to minimize the scarcity of water. Therefore, this study shall come up with the appropriate wastewater treatment system that can be applicable to seed-producing industries. The technology shall be able to treat the wastewater produced from seed producing industries and the treated wastewater can be functional for irrigation activity. Furthermore, based on the findings of this research seed-producing industries shall apply this sustainable, effective, environmentally friendly and low cost wastewater treatment technology to treat their wastewater form their seed production process.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Africa is the second-largest continent in the world characterized by rapid population growth and urbanization. Because of an increase in population and economic growth, quantity of water consumption and wastewater disposal is increasing and leading to pollution (Wang *et al*., 2014). Moreover, water is becoming a scarce resource due to a lack of adequate wastewater treatment, reuse, and climate change in the continent (Wang *et al*., 2014). Industrial wastewater contributes greatly to aquatic pollution followed by municipal and agricultural wastewaters (Hagberg, 2007). The pollution from industries occurs because of releasing untreated or ineffectively treated wastewater into the environment. Wastewater treatment plants are intended to treat wastewaters from industries, domestics, or agricultural activities. However, for the systems to function properly, it needs an appropriate selection of wastewater treatment technology based on the wastewater characteristics, loading rate, and climate condition.

A large number of industries in Africa do not have a wastewater treatment system but few of them treat their wastewater using either waste stabilization ponds or septic tanks (Wang *et al*., 2014). However, these treatment systems are failing to remove pollutants from industrial wastewater to meet the stipulated standard for industrial effluent. According to studies done by Miguel *et al*. (2004) most wastewater treatment plants do not function effectively because of insufficient knowledge in considering all local factors during designing and selecting the appropriate wastewater treatment system. Besides, limited information and experience in the field cause industries not to use appropriate technologies to treat their wastewater (Wang *et al*., 2014). As a result, environmental pollution is expanding and public health is in threat.

Waste stabilization ponds are the most popular industrial wastewater treatment system in the continent (Wang *et al*., 2014). In Tanzania, waste stabilization ponds are typically wastewater treatment systems for domestic and industrial wastewaters (Mbwele *et al*., 2004). According to the study by Mbwele *et al*. (2004) waste stabilization pond treatment removes pollutants partially and the effluent quality does not meet the world health organization (WHO) standard for discharging the wastewater into the environment. The first factor, which makes the wastewater that has been treated in the stabilization pond not meet the required standard, is because of the absence of pre and post-treatments combined with the stabilization ponds. As a result stabilization pond fails to remove some pollutants (Wang *et al*., 2014). Another reason for the failure of wastewater treatment systems comes from receiving high loaded wastewater containing high concentration of pollutants. Wang *et al*. (2014) recommended that to get effective wastewater treatment a combination of two or more technologies is required based on the wastewater characteristics. The combination can include anaerobic wastewater treatment systems with CWs.

2.2 Anaerobic baffled reactor (ABR)

Anaerobic treatments are primary treatment systems characterized by less energy consumption and less sludge production, which results in low operational and maintenance costs of the system (Alighardashi *et al*., 2015). Anaerobic baffled reactor is an anaerobic wastewater treatment system developed in the 1980s (Stuckey & Barber, 2000). The system is composed of vertical baffles. The bacteria in the reactor moves horizontally as wastewater passes through from influent to effluent and also it tends to rise when there is gas production this allows the wastewater to contact active biological mass in the system within a short HRT (Nguyen *et al*., 2010). Due to the unique design of ABR, HRT and the solids retention time (SRT) are separated in the reactor, which results in high rate of anaerobic treatment system (Dama *et al*., 2002). The easiness of the design with low HRT, the ability to sustain high organic loadings, toxics, and loading shocks make the system preferable. Furthermore, the system separates acidogenic and methanogenic bacteria in the reactor (Wang *et al*., 2004).

Nowadays, ABR is applicable from industrial to domestic wastewater treatment options. In the paper and pulp industry, ABR has shown successful performance in the removal of organics during the startup period (Alighardashi *et al*., 2015). Moreover, ABR performed efficiently in the removal of COD, suspended solids (SS), and sulfate (SO_4) as a pilot scale in treating dyeing wastewater after $FeSO_4$ pretreatment (Qi *et al*., 2019). Ferraz *et al*. (2009) and Movahedyan *et al*. (2007) obtained 92% organic matter removal efficiency from cassava biodegradable wastewater and 67% COD removal efficiency from wheat flour starch wastewater, respectively after the removal of suspended solids. Furthermore, ABR was able to treat successfully distillery wastewater from a scotch whiskey factory on a laboratory scale (Boopathy *et al.*, 1988).

For domestic wastewater treatment, ABR showed good performance in COD and TSS removal. For example, Nasr *et al*. (2009) obtained removal efficiency of 68% - 82% for COD and 73.4% - 82% for TSS from domestic wastewater with an organic loading rate of 2.1 kg COD/m^3 day and 8 to 24 hours of HRT. Minh and Phuoc (2014) also reported overall efficiency of 72% - 74% for COD and 89% - 99% for TSS from domestic wastewater with an influent TSS and COD concentration of 80 mg/L – 290 mg/L and 176 mg/L – 352 mg/L, respectively.

In general, ABR wastewater treatment system is efficient in terms of energy and cost. Organic matters and TSS are removed effectively from high strength wastewater in this system, however, due to anaerobic condition; it is not able to remove ammonium from the wastewater.

2.3 Constructed wetlands (CWs)

Constructed wetlands are designed similar to natural wetlands with a controlled environment. These systems are applicable as primary, secondary, or tertiary wastewater treatment (Bu & Xu, 2013; Stefani *et al*., 2011; Thalla *et al*., 2019; Vrhovšek et *al*., 1996). Constructed wetlands can be applicable in the municipal, domestic, agricultural, and industrial wastewater treatment processes. However, a careful analysis is needed before application since the system needs pretreatment for strong wastewater. Constructed wetlands are classified into different types based on hydrology, flow path, and macrophytic growth form. From the hydrology of the CWs, there are two types subsurface flow and surface flow. According to the wastewater flow direction, CWs are classified as vertical, and horizontal and based on the microphytic growth, CWs can be emergent and submergent (Fig. 2).

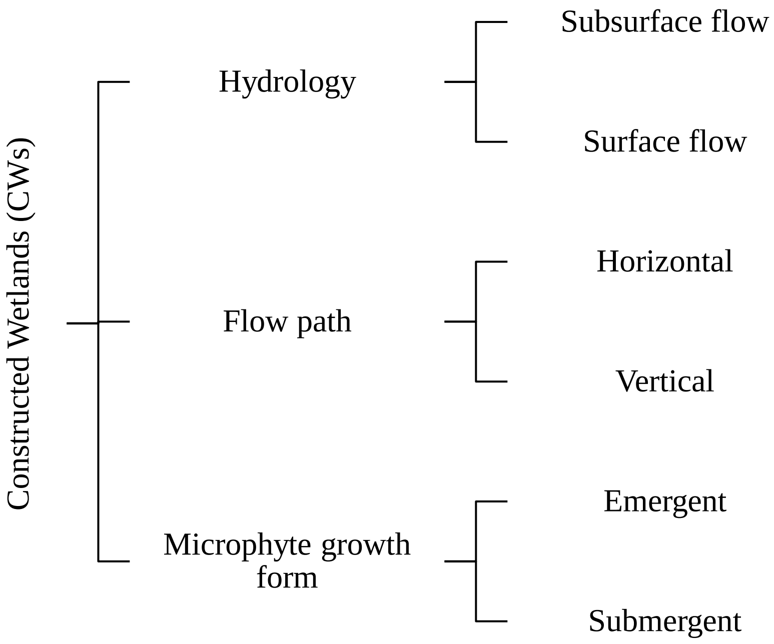


Figure 2: Types of constructed wetlands

Different CWs were used for primary, secondary, and tertiary wastewater treatment. For the wastewater composed of high-suspended solids and other pollutants, there must be a primary treatment system for removal of suspended solids and reduction of loaded pollutants from the wastewater to prevent clogging. Some industries used single-stage constructed wetlands as a wastewater treatment system without having pretreatment or post-treatment and experienced system failure because of the high load of pollutants in the wastewater and suspended solids which clogged the system (Wang *et al.*, 2014).

2.3.1 Horizontal subsurface flow constructed wetlands (HSSFCWs)

Horizontal subsurface flow CWs are wastewater treatment systems that treat the wastewater as it flows under the surface of the substrate material through physical, chemical, and biological processes. Horizontal subsurface flow CWs are considered efficient in BOD_5, COD and TSS removal, however, limited to nutrient removal (Rangel *et al.*, 2007). The system has been applicable for pollutant removal from different industrial wastewater and showed high efficiency of organic removal but lower nutrient removal (Akratos & Tsihrintzis, 2006; Rangel *et al.*, 2007). Dissolved oxygen concentration in the CW bed is very limited as a result the nitrification process influenced and the removal efficiency of ammonium reduced in the system (Cottingham *et al*., 1999; Naja & Volesky, 2011; Rossmann *et al*., 2012). The removal of phosphorus depends on the substrate material used however phosphorus is not removed much compared to nitrogen (Khanijo, 2002).

Horizontal subsurface flow CWs cannot treat strong wastewater without pretreatment. The system is considered as a secondary or tertiary wastewater treatment system for strong wastewater and they are effective in the removal of organic matter and TSS. Therefore, even though HSSFCWs are sustainable, environmentally friendly, and low-cost wastewater treatment technologies, it is not advisable to use the systems for raw wastewater as a primary wastewater treatment system (El-Khateeb *et al*., 2009). Moreover, post-treatment is also important to enhance the nitrification process and removal of nitrogen from the wastewater. A study by Singh *et al*. (2009) for the municipal wastewater treatment system, HSSFCW showed 69.3% TSS, 57.5% BOD_5, and 51% COD removal efficiency. Vrhovšek *et al*. (1996) studied the performance of HSSFCW in the removal of pollutants from food processing industrial wastewater after the sedimentation basin. The flow rate of the wastewater was 5 m^3/d and the influent BOD_5 and COD values were 962 mg/L and 3674 mg/L, respectively. The results showed 92%, 89%, 86%, and 65% removal efficiency for BOD_5, COD, ammonium and nitrate, respectively. Furthermore, the performance of pilot-scale HSSFCW was studied by Thalla *et al*. (2019) as a tertiary treatment stage for secondary effluents. The results were 77% of BOD_5, 83% of COD, 60% of NH_4^+-N, 67% of NO_3^--N, and 69% of PO_4^{3-}-P removal efficiency.

Overall, HSSFCWs are very efficient in removal of BOD_5, COD, and TSS. However, the system has a limitation in nutrient removal and the nitrification process is limited due to the limited availability of oxygen at the HSSFCW bed.

2.3.2 Floating constructed wetlands (FCWs)

In the FCW, the plants float on the surface of the wastewater. The root biofilm network has a large contact with the wastewater passing through the system which enabled the plants to assimilate nutrients directly from the polluted wastewater (Headley & Tanner, 2008). The pollutant removal processes are physical and biological through a combination of microbial activity and plants.

Several studies have been done on the performance of FCW in the removal of pollutants from different wastewater. For example, FCW was studied for the removal of phosphorus from storm water and the result obtained showed that FCW was able to remove phosphorous with an average efficiency of 27% (Borne, 2014). The removal of phosphorous in FCW was achieved by plant uptake, sorption of dissolved phosphorous, physical entrapment in roots, and settlement. Furthermore, a study was done to treat eutrophic river using FCW and results obtained showed that for influent eutrophic river water with 6.5 – 18.5 mg/L COD, 6.8 – 12.3 mg/L TN, and 0.7 – 1.6 mg/L TP the removal efficiency was 15.3% - 38.4% COD, 25.4% - 48.4% TN, and 16.1% - 42.1 % TP (Bu & Xu, 2013). The performance of FCW on pollutant removal from aquaculture effluent was studied by Stefani *et al*. (2011) and the results showed that the system performed 66% COD removal, 52% BOD_5 removal, and 65% total phosphorus removal efficiency. Moreover, a pilot-scale FCW was studied for a tropical climate, and the performance of the system was found to be 40% for NO_3^- removal, 80% for BOD_5 and 80% for NH_4^+ - N removal efficiency (Weragoda *et al*., 2012).

Generally, FCWs are aerobic wastewater treatment technologies, which can facilitate the nitrification process and remove ammonium from the wastewater.

2.4 Integrated wastewater treatment systems

Combing different wastewater treatment technologies gives efficient removal of pollutants from high loaded wastewater. Single staged CWs are unable to give effective removal of nitrogen pollutants from the wastewater due to their limitation to give aerobic and anaerobic conditions at the same time (Vymazal, 2007). For effective removal of pollutants particularly nutrients, HSSFCWs need to be combined with other tertiary treatment technologies such as FCW, vertical subsurface constructed wetland (VSSFCW) and ponds (Sayadi *et al*., 2012).

The hybrid CWs have been studied for years. The combination of HSSFCW and VSSFCW have been used for different industrial wastewater treatment (Sayadi *et al*., 2012). The performance of the hybrid wetland in removal efficiency was not satisfactory especially when it comes to nutrients in the wastewater. The effective performance of a hybrid constructed wetland comes when it integrates with good pretreatment which will remove the pollutants to avoid loading of pollutants and clogging of the CWs (Varga *et al*., 2016).

In a detergent and soap industry, a combination of HSSFCW and VSSFCW was used to treat the wastewater. The arrangement was two parallel VSSFCW in the middle with HSSFCW placed at the beginning and at the end of the system. The removal efficiency was 67% for COD, 66% for $\mathrm{BOD_5}$, 63% for phosphorus, and 83% for nitrate (Justin *et al*., 2009). Moreover, in the fertilizer and chemical manufacturing industry, the combination of VSSFCW and HSSFCW was used for treating wastewater and the removal efficiency was 96% for $\mathrm{NH_4^+}$, 65% for TN, and -10.2% for $\mathrm{NO_3^-}$ (Domingos, 2011). The negative removal efficiency of $\mathrm{NO_3^-}$ was due to the high conversion of $\mathrm{NH_4^+}$ in the VSSFCW and low denitrification of $\mathrm{NO_3^-}$ in the HSSFCW stage. Xiong *et al*. (2011) evaluated the performance of an integrated wastewater treatment system consisted of VSSFCW, floating bed, and sand filter. The removal efficiency of the system was 98.8%, 95.6%, and 98.1% for $\mathrm{NO_3^-}$ - N, $\mathrm{NO_2^-}$ - N, and $\mathrm{NH_4^+}$- N, respectively and effective removal of nitrogen pollutants in the integration system was achieved due to the use of peat as a source of carbon for denitrifying bacteria.

The combination of free water surface flow wetland with subsurface flow wetland was studied by El-Khateeb *et al*. (2009) in the removal of pollutants from raw sewage effluent after up-flow sludge blanket pretreatment. The results showed that the hybrid wetland was able to remove pollutants with an efficiency of 69% for COD, 70% for $\mathrm{BOD_{5,}}$ and 67% for TSS (El-Khateeb *et al*., 2009). Moreover, hybrid CWs consisting of HSSFCW and VFCW after anaerobic pretreatment was studied by Singh *et al*. (2009) and the integrated system achieved an average removal efficiency of 95.9% for TSS, 90.1% for $\mathrm{BOD_5}$, 90% for COD, 69.5% for $\mathrm{NH_3}$-N, and 26.1% for TP.

To overcome the problem of wastewater treatment system failure and low performance in the removal of pollutants different treatment technologies must be integrated. This will minimize environmental pollution, which resulted from the disposal of partially treated or untreated wastewater. However, the combination of the system needs a deep understanding of the characteristics of the pollutant, and the strength and the weakness of each system. This will allow the system to function as expected. Therefore, in this study, the performance of HSSFCWs integrated with ABR and FCW in pollutant removal was studied.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study site

The study was conducted at Enza Zaden seed-producing industry located in Arusha, Tanzania at 3^{o}24’0.521” S latitude and 36^{o}47’16.256” E longitude with an elevation of 1192 m above mean sea level (Fig. 3). The industry produces vegetable seeds such as sweet pepper, paprika, cucumber, and tomato. In the production process, wastewater is generated from washing of the seeds after extraction. The effluent from seed production is generated at a rate of 20 to 30 m^3 per day and stored in wastewater reservoir with a volume of 340 m^3. It is then treated in ABR before being transferred to HSSFCW and FCW for secondary and tertiary treatment, respectively. The system was newly built and started operation in June 2020. The study on investigating the performance of the integrated system was conducted for three months from June to August 2020.

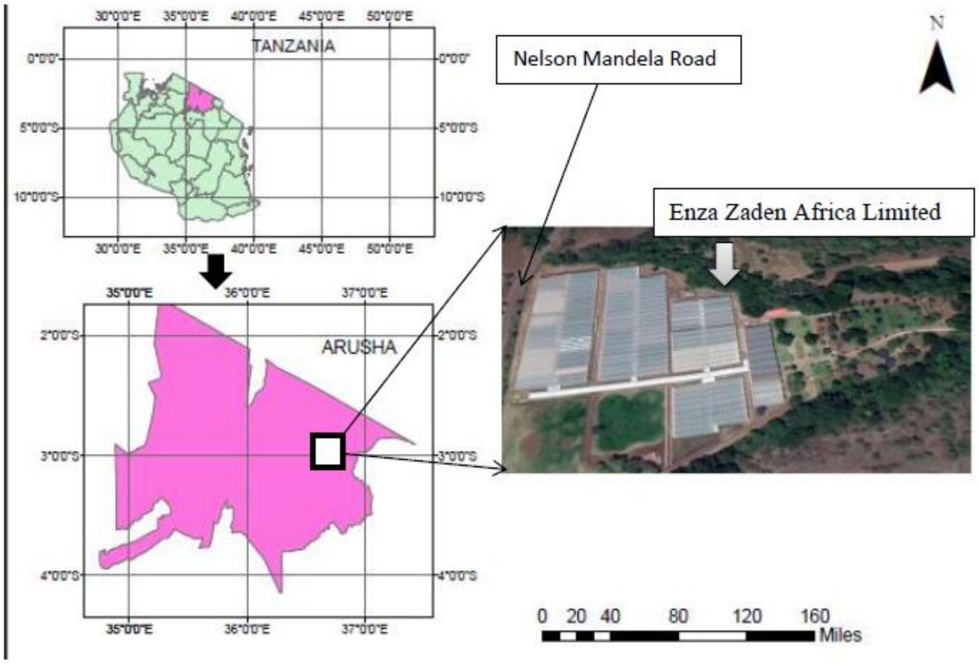


Figure 3: Study site

3.2 Anaerobic baffled reactor unit

The ABR unit is composed of six compartments with a total volume of 205.3 m^3. Each compartment has the same cross-sectional area. The raw wastewater was treated primarily in this unit. During the study period, the system was receiving 25 m^3 of wastewater per day from the equalization tank. The dimension and operating conditions of the system are included in Fig. 4 and Table1.

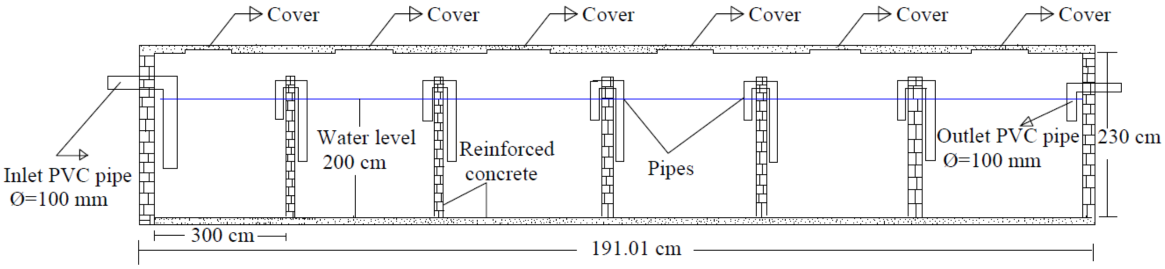


Figure 4: The cross-sectional area of ABR unit

3.3 Horizontal subsurface flow constructed wetland unit

Horizontal subsurface flow CW receives pretreated wastewater from ABR and discharges the effluent to FCW for tertiary treatment. The HSSFCW is filled with clean aggregates with a diameter of 12 – 20 mm and an average porosity of 0.35. The native African aquatic flowering plant known as *Cyperus alternifolius* was used. The rhizomes were collected from nearby natural wetlands and planted three rhizomes/m^2. The influent was allowed to flow horizontally through gravels and plants until it reaches the exit. The detailed cross-section and configuration of HSSFCW are shown in Fig. 5.

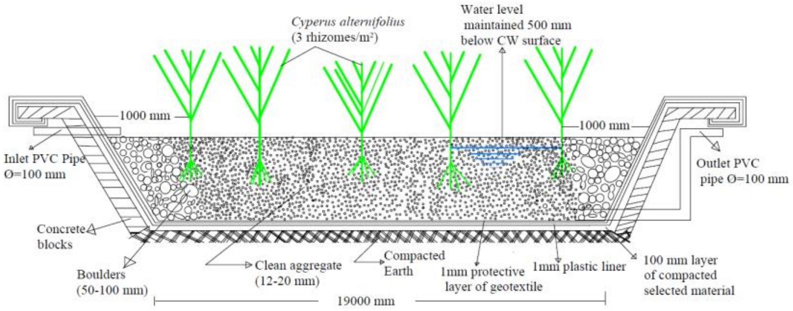


Figure 5: The cross-sectional area of HSSFCW unit

3.4 Floating constructed wetland unit

The final and tertiary treatment system is FCW. It has four floating mats made from polyethylene foam plate each with an area of 3.75 m^2 and fixed 4 m distance apart (Fig. 6). The mat is covered by Vetiver grass *(Vetiveria zizanioides).* Dimension and operational conditions for FCW are described in Table 1.

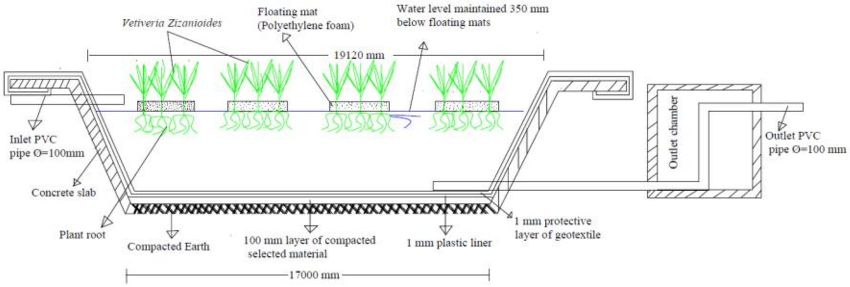


Figure 6: The cross-sectional are of FCW

Figure 7 shows the integrated wastewater treatment system, which was installed at Enza Zaden. The integration coupled ABR as primary treatment unit, HSSFCW as a secondary treatment unit and finally FCW as a tertiary treatment unit.

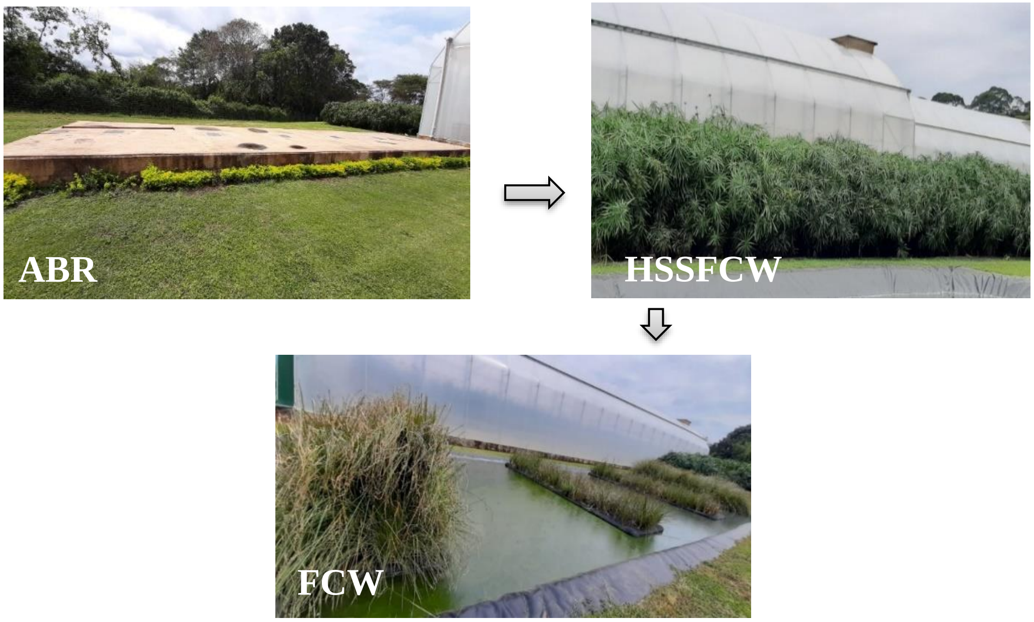


Figure 7: Integrated wastewater treatment system

Table 1: Dimensions and operating conditions of each system

Dimensions	**ABR**	**HSSFCW**	**FCW**
Length (total), m	19.01	19.3	19.12
Length of the treatment zone , m	18.75	19	17
Length of inlet and outlet zones, m	0.26	0.3	0.12
Width, m	3.6	8	8
Depth of water, m	2	0.5	0.35
Operating conditions			
HRT^{a}, days	5	3.8	4.5
OLR^{b}_{range} , kg-$\mathrm{BOD_5/m^3d}$	0.114 – 0.174	0.026 – 0.118	0.011 – 0.079
$\mathrm{OLR}^{b}_{average}$, kg-$\mathrm{BOD_5/m^3d}$	0.134	0.068	0.032
OLR^{b}_{range}, kg-COD/$\mathrm{m^3d}$	0.179 – 0.262	0.049 – 0.211	0.016 – 0.221
$\mathrm{OLR}^{b}_{average}$, kg-COD/$\mathrm{m^3d}$	0.208	0.102	0.061

[a] Hydraulic Retention Time

[b] Organic Loading Rate

3.5 Sampling

Wastewater samples from the inlet and outlet of each treatment system were collected twice a week and the sampling techniques followed the recommended standard methods for examination of water and wastewater (APHA, 2017). A total of one hundred and eight samples were collected. The sampling was done using pre-cleaned 100 ml polyethylene sampling bottles. The bottles were prepared by soaking in a 5% HCL overnight and then after rinsed 3 to 5 times with distilled water in the laboratory. In the field, before sampling, the bottles were rinsed 3 to 5 times with the same wastewater to be collected. After sampling the samples were stored in a cool icebox at $4^{\mathrm{O}}\mathrm{C}$ and transported to the Nelson Mandela African Institution of Science and Technology laboratories for analysis.

3.6 Physicochemical analysis

All parameters were analyzed based on the standard methods for examination of water and wastewater (APHA, 2017). Wastewater parameters such as pH, temperature, electric conductivity (EC), and total dissolved solids (TDS) were measured in-situ using Hanna Multiparameter (HI

9829). The turbidity of the wastewater was analyzed by Microprocessor Turbidity Meter (HI 93703). Additionally, the cadmium reduction method was used to analyze nitrate and nitrite, and ascorbic acid powder pillow method was used for analyzing phosphate using HACH DR 2800 spectrophotometer. Furthermore, the Nessler reagent method was used to analyze ammonia and ammonium while COD was analyzed by the reactor digestion method. Biochemical oxygen demand was analyzed by a closed manometric method.

3.7 Data analysis

Origin pro 9.0 version and Microsoft Excel were used for data analysis. The trend of pollutants in each treatment unit and the removal efficiency were obtained. The efficiency of the system in the removal of pollutants was calculated by using Equation 1.

$$\mathrm{R}(\%) = \left(\frac{\mathrm{C_i}-\mathrm{C_f}}{\mathrm{C_i}}\right) * 100 \tag{1}$$

Where R is percentage removal efficiency and $\mathrm{C_i}$ and $\mathrm{C_f}$ are the initial and final concentration of pollutants, respectively.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Performance of each treatment unit in the treatment chain

4.1.1 Characteristics of the wastewater

Data for inflow and outflow from each unit are presented in Table 2. Based on the characteristics the raw wastewater can be classified as high strength wastewater (Metcalf & Eddy, 2004). The BOD_5/COD ratio was in a range between 0.6 - 0.8 this shows the high biodegradability level of the wastewater (Zaher & Hammam, 2014).

Table 2: The average concentration of pollutants at each treatment stage

		Raw		ABR		HSSFCW		FCW	
Parameters	Units	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.
TSS	mg/L	373	23.8	197.4	30	68.8	20.5	51.4	23
Turbidity	FTU	47.7	5	34.9	5.6	16.3	5.9	11.2	4.8
BOD_5	mg/L	688.8	95.7	206.0	81.4	59.4	35.2	26.2	12.4
COD	mg/L	1074	130.5	301.6	135	107.7	83	58.3	39.7
NO_3^-	mg/L	376.9	87.5	332.9	86.5	173.8	49.1	66.3	25.8
NO_2^-	mg/L	0.95	0.2	0.8	0.2	0.6	0.2	0.4	0.1
NH_4^+	mg/L	123.6	18.4	141.5	18	122.3	15.4	106.3	18.7
PO_4^{3-}	mg/L	60.2	11.5	52.9	10.3	29.7	8.7	14.2	5.8

S.D. is Standard Deviation

4.1.2 Performance of anaerobic baffled reactor

Table 3 shows the average influent and effluent physicochemical characteristics of the wastewater in the ABR treatment stage. The temperature of the wastewater was ranging from 21.9 to 28°C and 21.2 to 26.6°C at the influent and effluent, respectively. The temperature variation in this treatment stage was within the optimal temperature range for effective biological activity. Temperature is a key parameter in biological wastewater treatment systems and the variation in temperature affects the rate of microbial activity in the treatment process (Kadlec & Reddy, 2001). Microorganisms in the wastewater treatment systems function effectively within 20 to 35^{o}C temperature range.

Table 3: Physicochemical parameters of the wastewater at the influent and effluent of ABR

Parameters	Influent		Effluent	
	Average	S.D.	Average	S.D.
Temperature (^{o}C)	23.5	1.6	24.1	1.5
pH	6.8	0.3	6.9	0.2
EC (µs/cm)	1924	213.5	1966	241.2
TDS (mg/L)	962.2	106.8	984.1	120.2

The pH of wastewater is an important factor in chemical and biological treatment processes. The average pH in the influent and effluent of the ABR treatment stage was 6.8 ± 0.3 and 6.9 ± 0.2, respectively (Table 3).

The TDS values of influent and effluent in ABR ranged from 681 mg/L – 1134 mg/L, 691 mg/L – 1204 mg/L, respectively; whereas the EC ranged from 1362 µs/cm – 2268 µs/cm, and 1382 µs/cm – 2404 µs/cm at the influent and effluent, respectively (Fig. 8). Total dissolved solids and EC increased slightly from inlet to outlet. This was attributed by the degradation of pollutants from the wastewater and dissolutions of ions (Mtavangu *et al*., 2017). Moreover, an increase of TDS and EC might also be contributed by mineralization i.e. the conversion of organic carbon into a smaller and simple organic compound.

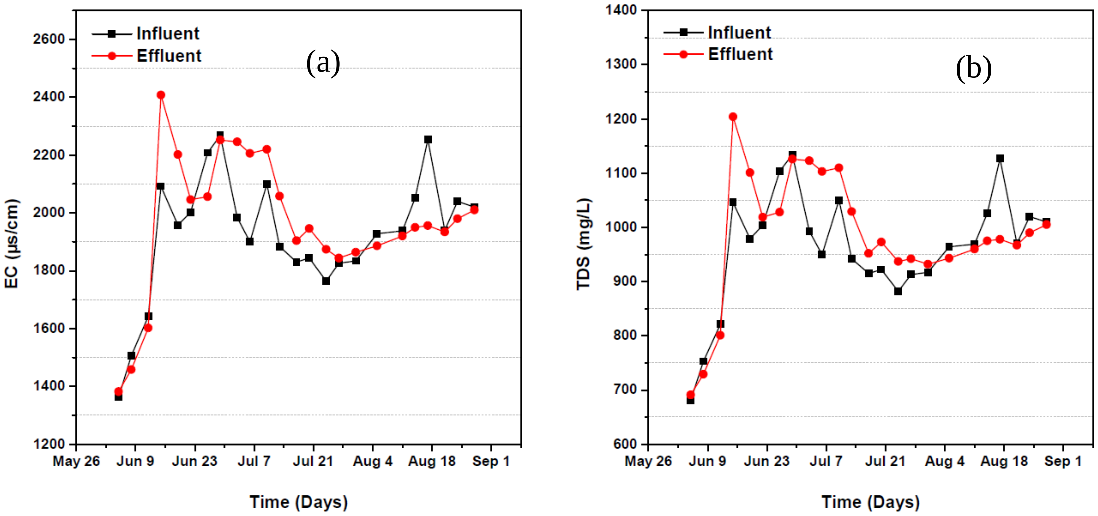


Figure 8: The variation of (a) EC (b) TDS with time in ABR

Figure 9(a) shows the variation of TSS at the influent and effluent of ABR system. The concentration of the TSS in the influent and effluent ranged from 337 mg/L to 420 mg/L and 27 mg/L to 112 mg/L, respectively. Anaerobic baffled reactor showed an average removal efficiency of 47 ± 8.3% for TSS (Table 4). The performance of ABR in the removal of TSS in this study was higher than the study by Qi *et al*. (2019) who obtained 39.9% TSS removal efficiency from dyeing wastewater using a pilot-scale ABR with 6 compartments, 12 hours HRT and 18 m^3 total volume. The better performance of ABR in the current study might be due to the larger size and HRT of ABR (205.3 m^3 volume and 5 days HRT).

The occurrence of suspended, dissolved particles, organic, and inorganic matters in wastewater make the wastewater turbid. The results in Fig. 9(b) shows the variation of turbidity concentration at the influent and effluent of ABR. The influent turbidity ranged from 39 to 57 FTU however, the value decreased in a range between 22.6 and 45 FTU at the effluent. The decrease in turbidity might be due to the retention of particulate matter in the system (Ferraz *et al*., 2009). The average turbidity removal efficiency of 26.6 ± 9.9% was obtained.

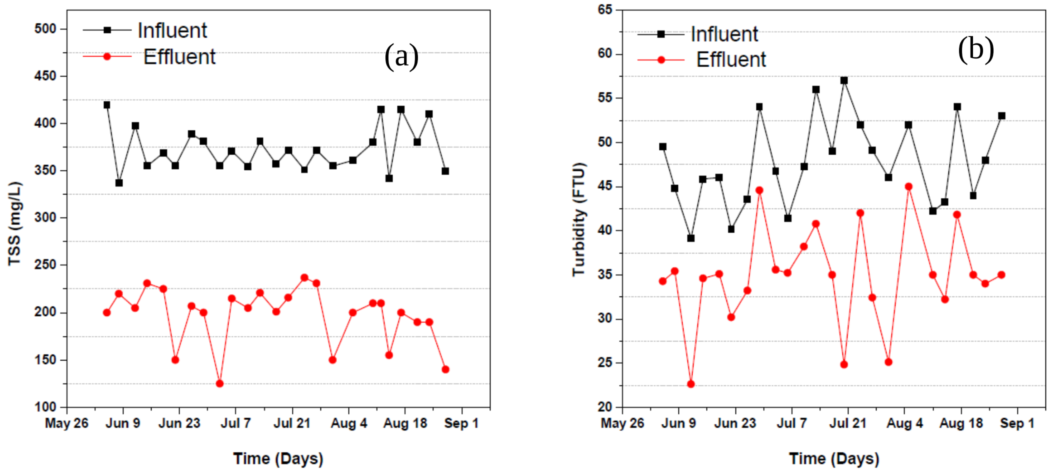


Figure 9: The variation of pollutants with time in ABR (a) TSS (b) Turbidity

In ABR microorganisms degrade organic matter into methane and carbon dioxide (Dinsdale *et al*., 2007). The concentration of COD and BOD_5 in the influent and effluent are shown in Fig. 10(a) and (b). The concentration of COD in the influent and effluent ranged from 930 mg/L -1360 mg/L and 148 mg/L – 640 mg/L, respectively. The removal efficiency of COD was in a range from 31.2% - 88.5% with an average removal efficiency of 71.6% ± 13.6%. In the beginning, the removal efficiency was below 50% then after one-month of operational period, it increased to 88.5%. This might be due to the period which microorganisms were establishing themselves in the system.

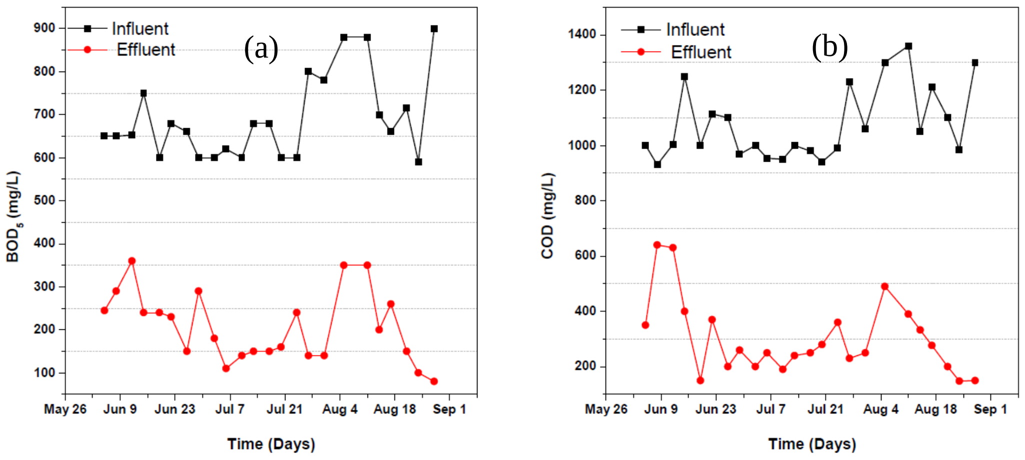


Figure 10: The variation of pollutants with time in ABR at the influent and effluent (a) BOD_5 (b) COD

Table 4: Percentage pollutant removal efficiency of ABR

Parameters	Efficiency (%)		
	Range	Average	S.D.
TSS	32.5 – 64.8	47	8.3
Turbidity	13.5 – 56.4	26.6	9.9
BOD_5	44.9 – 91.1	70.6	11.7
COD	31.2 – 88.5	71.6	13.6
NO_3^-	0 – 26	12	7.4
NH_4^+	-38.9 - -0.8	-15.3	11.1

The performance of ABR in this study for COD removal was comparable to other similar studies, for example, Ferraz *et al*. (2009) obtained 83% removal efficiency of COD in the treatment of cassava biodegradable wastewater for 3.5 HRT and 2 g COD $L^{-1}d^{-1}$ OLR. Also, Minh and Phuoc (2014) obtained 72% - 74% COD removal efficiency in the treatment of domestic wastewater at OLR 1.5 – 2.7 kg COD/m^3d and 3 hours HRT. Moreover, the performance of ABR in the removal of COD in this study was higher than the study by Hahn and Figueroa (2015) who obtained an efficiency of 15% - 43% COD removal in the treatment of raw municipal wastewater with influent COD concentration ranging from 760 mg/L to 190 mg/L.

Influent and effluent BOD_5 concentration in ABR ranged from 591 mg/L to 900 mg/L and 80 to 360 mg/L, respectively with removal efficiency of 90.8% - 99.1%. The performance of ABR for BOD_5 removal efficiency in this study was higher than 82% reported by Mahenge and Malabeja (2018) for municipal wastewater treatment in Tanzania, which had an average influent BOD_5 concentration of 314 mg/L. In this study, it was observed that at the start, ABR unit showed low removal efficiency for COD and BOD_5 parameters however, the removal efficiency increased with time (Fig. 9).

Figure 11 shows the variation of ammonium and nitrate concentration with time in ABR. The influent and effluent nitrate concentration was in the range of 265 mg/L – 585 mg/L and 200 mg/L – 515 mg/L, respectively. Reduction of NO_3^- observed was due to the occurrence of denitrification, which remove NO_3^- as nitrogen gas by denitrifying bacteria (Stuckey & Barber, 2000). However, the nitrate removal efficiency was low (12 ± 7.4%) compared to the one occurred in HSSFCW

(46.8± 11.9%) and FCW (61.5 ± 11.7%). The low nitrate removal efficiency might be due to limited occurrence of organic carbon, which is an essential nutrient for denitrifying bacteria to convert nitrate to nitrogen gas.

Influent and effluent NH_4^+ concentration varied in a range of 88 mg/L – 158 mg/L and 101 mg/L – 171 mg/L, respectively. There was an increase of NH_4^+ at the effluent, this was because the ammonium that was released during the break down of organic matter by anaerobic bacteria was not oxidized into nitrite and nitrate as a result of the anaerobic environment (Hahn & Figueroa, 2015; Mahenge & Malabeja, 2018). Moreover, dissimilatory reduction, anaerobic respiration of microorganisms using NO_3^- as electron acceptor and reducing it into nitrate and ammonium leads to the formation of NH_4^+ (Semba *et al*., 2020).

$$NO_3^- \longrightarrow NO_2^- \longrightarrow NH_4^+$$

The average removal efficiency of -15.3 ± 11.1% was obtained due to an increase of ammonium at the effluent.

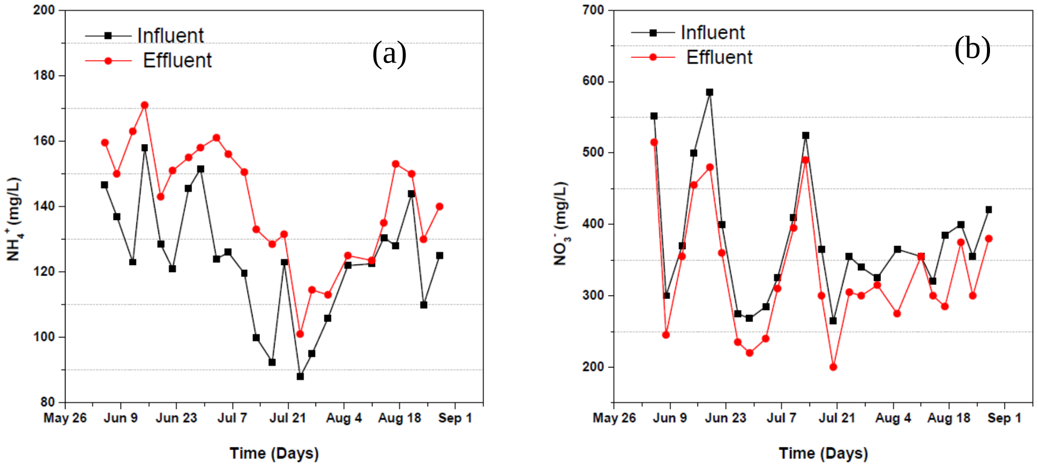


Figure 11: The variation of pollutants in ABR with time at the influent and effluent (a) NH_4^+ (b) NO_3^-

4.1.3 Performance of horizontal subsurface flow constructed wetland

Table 5 shows the physicochemical characteristics of the wastewater at the influent and effluent of the HSSFCW treatment stage. The temperature of influent wastewater ranged from 22.4 to

28.3^{o}C. Whereas the effluent temperature was ranging from 21.2 to 26.6^{o}C (Fig. 12b). Generally, a decrease in temperature at the effluent was observed this might be due to the atmospheric temperature variation in the field. However, the temperature ranges at the influent and effluent of the system were within optimum temperature range for effective microorganism activity in the treatment system.

The pH at the influent and effluent ranged 6.5 – 7.4 and 6.8 – 7.7, respectively (Fig. 12a). The pH increased at the effluent of the treatment unit. The increase in pH might be due to microorganism activity during the degradation of organic matter in the wastewater and the presence of the denitrification process (Xiong *et al.*, 2011). During degradation of organic matter from the wastewater, there is a release of ammonia and when ammonia dissolve in water it produce ammonium and OH^- ion. Also, in denitrification process the denitrifying bacteria consume organic carbon from the wastewater as nutrient and the process release alkalinity in the form of $CaCO_3$ that result in pH increment. Moreover, in HSSFCW intensive photosynthesis by emerged plants can also increase the pH due to the consumption of H^+ and CO_2 from the wastewater by plants (Yin *et al.*, 2016). However, the pH values at influent and effluent were within optimum pH range (6.5 – 8.5) for the biological wastewater treatment process (Metcalf & Eddy, 2004).

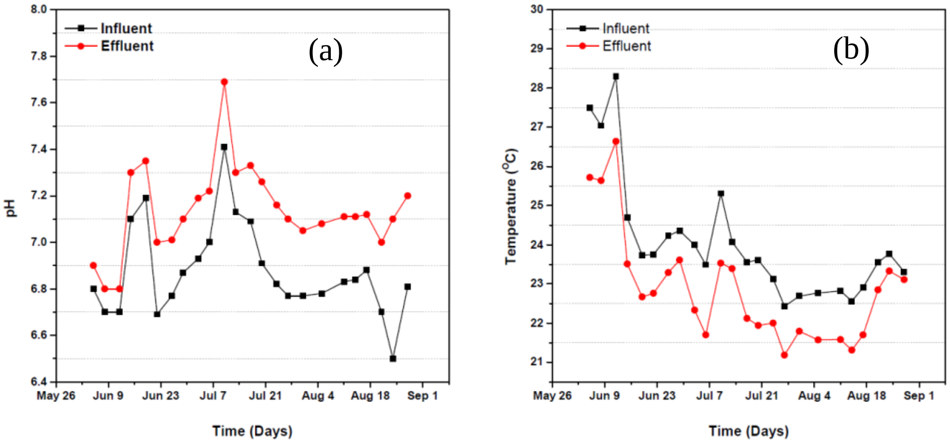


Figure 12: The variation of (a) pH and (b) Temperature in HSSFCW with time at the influent and effluent

Table 5: Physicochemical parameters of the wastewater at the influent and effluent of HSSFCW

Parameters	Influent		Effluent	
	Average	S.D.	Average	S.D.
Temperature (^{o}C)	24.1	1.5	22.9	1.4
pH	6.9	0.2	7.1	0.2
EC (µs/cm)	1966	241.2	2034	200.6
TDS (mg/L)	984.1	120.2	1017	100.3

In HSSFCW TDS varied from 691 mg/L to 1204 mg/L at the influent and 759 mg/L – 1214 mg/L at the effluent (Fig. 13b). Moreover, EC was 1382 µ/cm – 2408 µ/cm, and 1518 µs/cm – 2428 µ/cm at the influent and effluent, respectively (Fig. 13a). The increase of TDS and EC was observed from inlet to outlet. This was attributed by the degradation of pollutants from the wastewater in the treatment system and dissolutions of ions (Mtavangu *et al*., 2017).

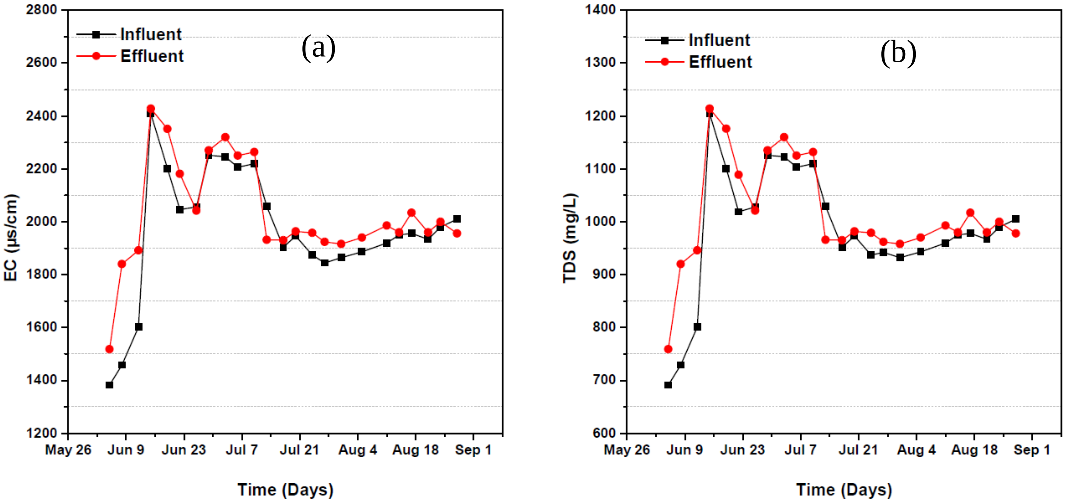


Figure 13: The variation of pollutants with time in HSSFCW (a) EC (b) TDS

Variation of TSS concentration and turbidity with time in the HSSFCW are presented in Fig. 14 and the percentage removal efficiency is shown in Table 6. The concentration of TSS in the wastewater ranged from 125 mg/L – 237 mg/L and 27 mg/L – 112 mg/L at the influent and effluent of the treatment stage, respectively. The observed average TSS removal efficiency was 64.7 ± 10.2%. The reduction of TSS in this stage is mainly through sedimentation of the suspended solids into the CW bed and filtration. Figure 14(b) shows the variation of turbidity at the influent and effluent of HSSFCW. The influent and effluent turbidity ranged from 22.6 - 5 FTU and 5.5 – 29.8 FTU, respectively. The average turbidity removal efficiency of 53.5 ± 14.2% was achieved.

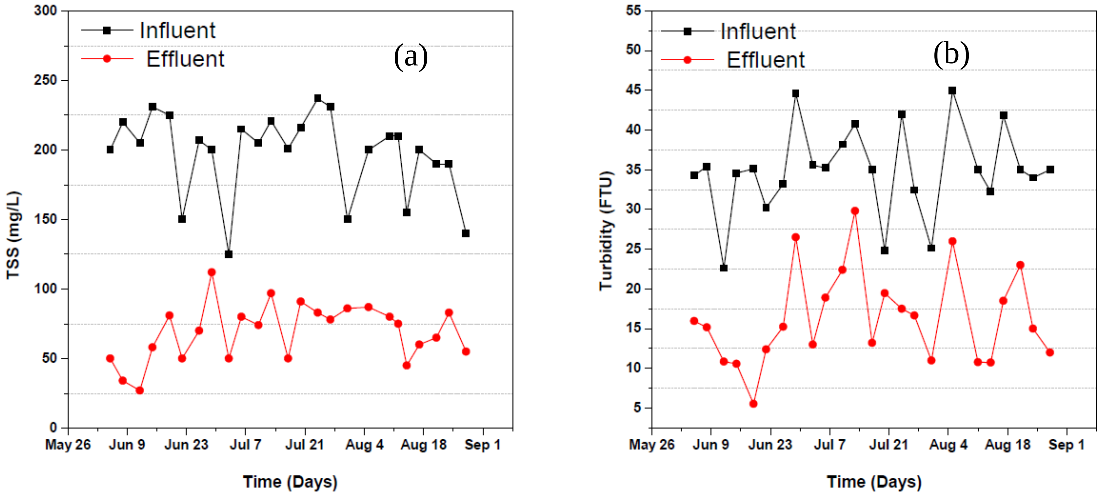


Figure 14: The variation of (a) TSS (b) turbidity pollutants with time in HSSFCW at the influent and effluent

The microorganisms attached to the root and rhizomes of the plant and on the substrate (gravel) degrade the organic matter in the wastewater. Variation of BOD_5 and COD with time in both the influent and effluent are presented in Fig. 15. The influent and effluent concentration of BOD_5 ranged from 80 mg/L – 360 mg/L and 20 mg/L – 150 mg/L, respectively. The average removal efficiency was 71.1 ± 10.6%. The concentration of COD in the influent and effluent ranged from 148 mg/L – 640 mg/L and 30 mg/L – 420 mg/L, respectively. An average COD removal efficiency of 65.7 ± 13.5% was obtained (Table 6). In this study, the performance of HSSFCW in the removal of TSS, BOD_5 and COD was higher than the one reported by Singh *et al*. (2009) on the removal of pollutants from high-strength municipal wastewater.

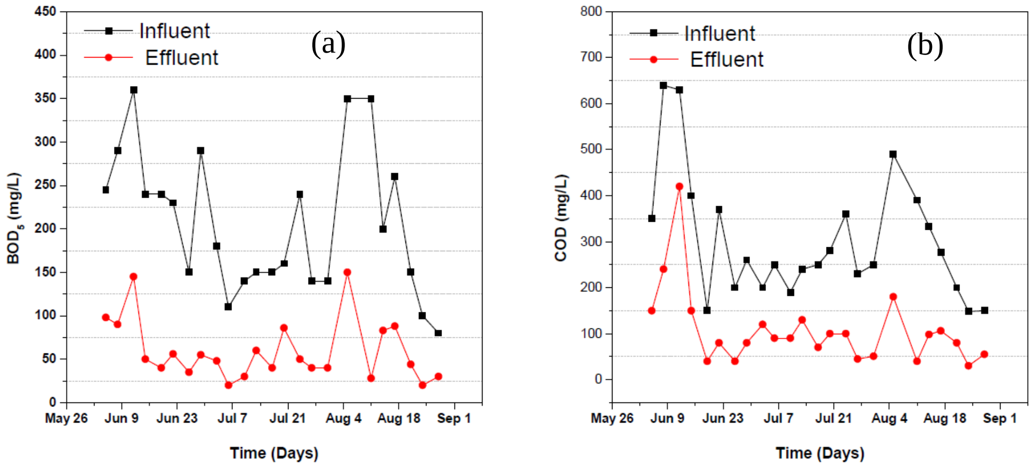


Figure 15: The variation of (a) BOD_5 (b) COD pollutants with time in HSSFCW at the influent and effluent

Table 6: The percentage pollutant removal efficiency of HSSFCW

Parameters	Efficiency (%)		
	Range	Average	S.D.
TSS	42.7 – 86.8	64.7	10.2
Turbidity	21.7 – 84.3	53.5	14.2
BOD_5	46.3 – 92	71.1	10.6
COD	33.3 – 89.7	65.7	13.5
NO_3^-	22 – 67. 6	46.8	11.9
NO_2^-	0 – 44.4	15	12.2
NH_4^+	1.13 – 30.8	13.2	8.6
PO_4^{3-}	21.31 – 64	43.7	12.4

Figure 16(a) shows the variation of nitrate concentration at the influent and effluent of HSSFCW. The concentration of NO_3^- in the influent and effluent varied in a range of 200 mg/L - 515 mg/L and 98 – 300 mg/L, respectively. In HSSFCW NO_3^- was removed by the denitrification process, plant uptake, sedimentation, and physical attachment. The average removal efficiency of 46.8 ± 11.9% was obtained. Moreover, influent and effluent NO_2^- concentration was ranging from 0.5 mg/L to 1 mg/L, and 0.3 mg/L to 0.9 mg/L, respectively (Fig. 16b). The average removal efficiency of 15 ± 12.2% was obtained. The removal efficiency of NO_2^- in HSSFCW was found to be small;

this might be due to the limited nitrification process because of limited oxygen in the system, which reduced the conversion of nitrite into nitrate.

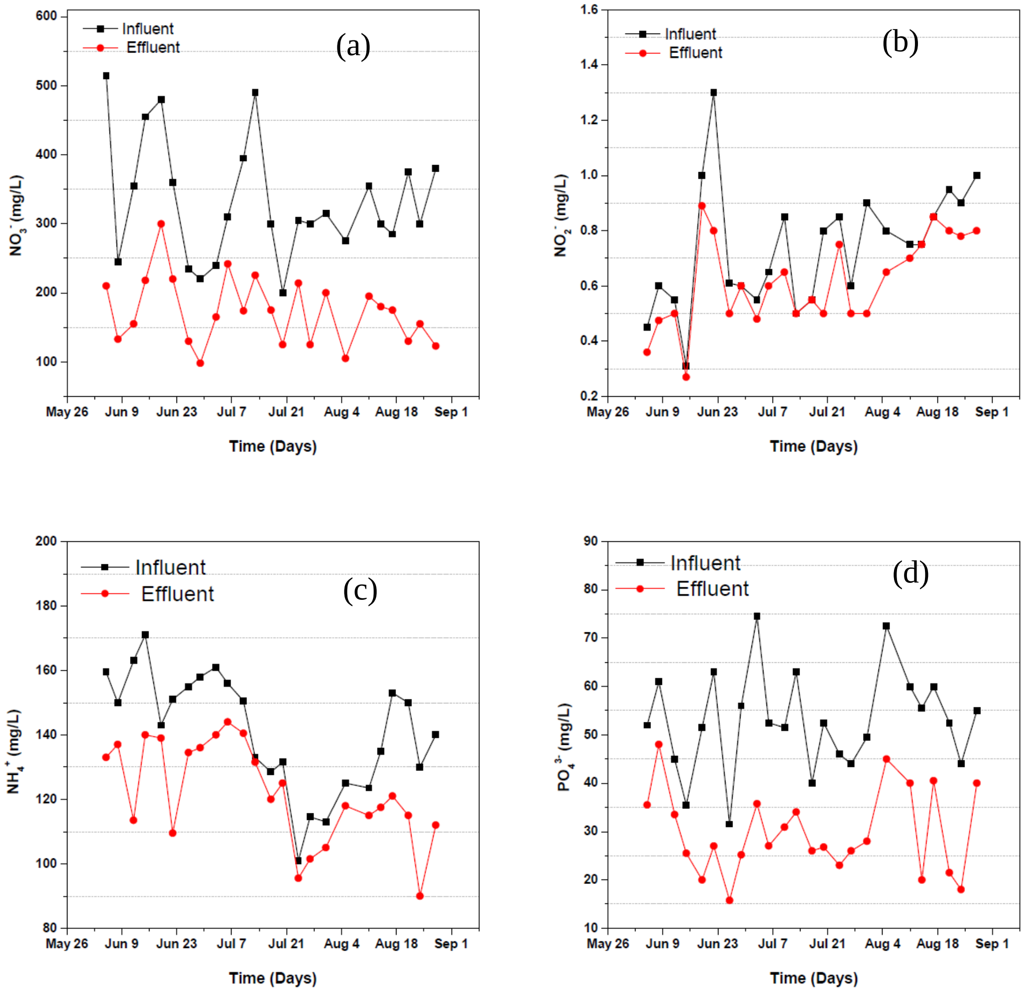


Figure 16: The variation of (a) NO_3^- (b) NO_2^- (c) NH_4^+ (d) PO_4^{3-} pollutants with time in HSSFCW at the influent and effluent

The concentration of ammonium in the influent and effluent varied in a range of 101 mg/L – 163 mg/L and 90 mg/L – 144 mg/L, respectively (Fig. 16c). The average removal efficiency of 13.2 ± 8.6% was obtained. In this study, the ammonium removal efficiency was found to be lower than that of BOD_5 and COD this was because the pathway of organic removal and biological nitrification contradicts in HSSFCW (Saeed *et al.*, 2014). The situation signifies that when there is a high rate of degradation of organic matter it depletes the available oxygen thus inhibit nitrification.

The removal of phosphorus in HSSFCW takes place through sedimentation, filtration, adsorption, and plant uptake (small amount). The concentration of PO_4^{3-} at the influent and effluent is presented in Fig. 16(d). The influent and effluent values ranged from 31.5 mg/L – 74.5 mg/L and 15.7 mg/L – 48 mg/L, respectively. The decrease in phosphate concentration at the effluent might be due to sorption on the surface of the substrate, sedimentation, and assimilation into biomass (Vrhovšek *et al*., 1996). The average removal efficiency of 43.7 ± 12.4% was obtained.

4.1.4 Performance of floating constructed wetland

Table 7 shows the average physicochemical characteristics of the wastewater at the influent and effluent of FCW treatment stage. The temperature of influent and effluent wastewater was ranging from 21.2 to 26.6°C and 19.4 to 27.1°C with an average value of 22.9 ± 1.4°C and 21.8 ± 2.1°C, respectively (Fig. 17b). The trend shows that there was decrease in temperature at the effluent this might be attributed by the atmospheric weather variation in the study site. The pH of influent and effluent was in a range of 6.8 to 7.7 and 7.2 to 8 with an average of 7.1 ± 0.2 and 7.5 ± 0.2, respectively (Fig. 17a). An increasing pH at the effluent might be due to microbiological activity; including the degradation of organic matter and intensive photosynthesis by floating pants (Yin *et al*., 2016).

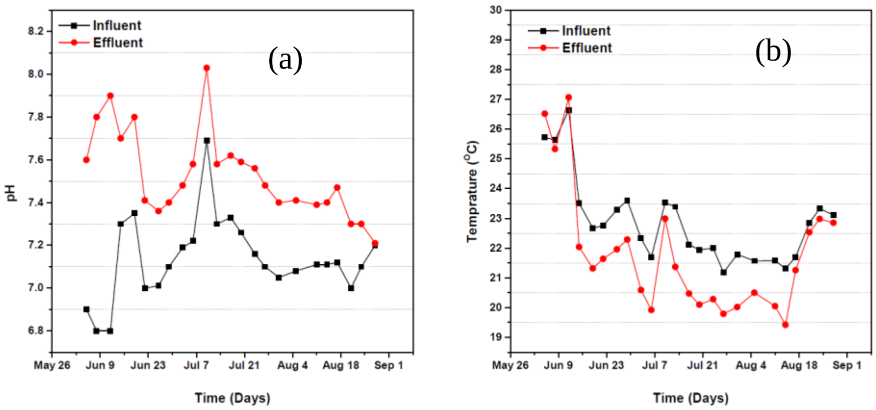


Figure 17: The variation of (a) pH and (b) Temperature in FCW with time at the influent and effluent

TDS at the influent and effluent was ranging from 759 mg/L – 1214 mg/L and 700 mg/L – 1275 mg/L, respectively (Fig. 18a). Meanwhile, the EC of influent and effluent wastewater varied in a range of 1518 µs/cm – 2428 µs/cm and 1400 µs/cm – 2550 µs/cm, respectively (Fig. 18b). There was a slightly increase of TDS and EC from influent; this might be due to the dissolution of ions during the breaking down of organic matter from the wastewater.

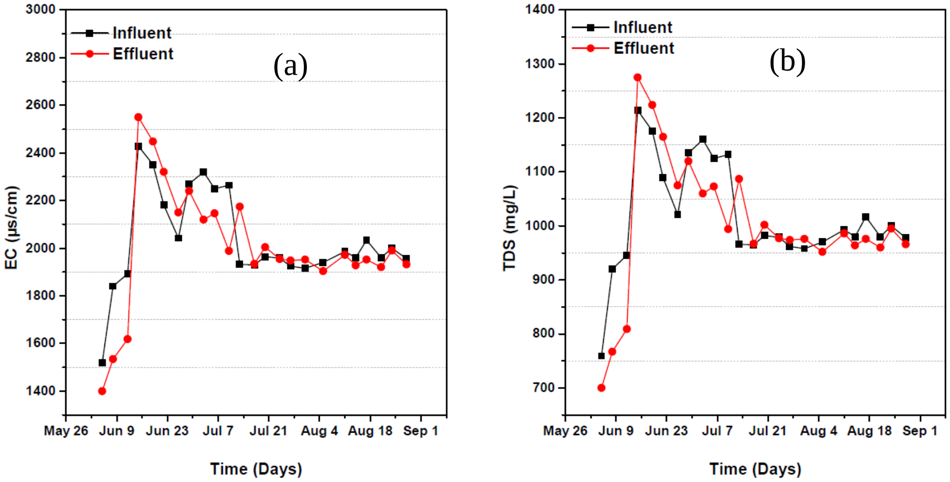


Figure 18: The variation of pollutants with time in FCW (a) EC (b) TDS

Table 7: Physicochemical parameters of the wastewater at the influent and effluent of FCW

Parameters	Influent		Effluent	
	Average	S.D.	Average	S.D.
Temperature (°C)	22.9	1.4	23.8	2.1
pH	7.1	0.2	7.5	0.2
EC (µs/cm)	2034	200.6	2043	256.6
TDS (mg/L)	1017	100.3	1022	128.6

Figure 19 shows the variation of TSS and turbidity concentration with time in FCW. Concentration of TSS in the influent and effluent ranged from 27 mg/L to 112 mg/L and 15 mg/L to 88 mg/L, respectively (Fig. 19a). The average removal efficiency was 28.3 ± 17.1% (Table 8). The roots of floating plants in the FCW trap suspended solids from the wastewater. Moreover, TSS was removed through sedimentation.

The removal efficiency of TSS in FCW was lower compared to the previous two stages this might due to the plant roots that are not well developed to capture the suspended solids since it is a newly established system and FCW does not have a filtering media like HSSFCW. The turbidity in the influent and effluent was in a range of 5.5 FTU – 29.8 FTU and 4.5 FTU – 22 FTU, respectively (Fig. 19b). The average turbidity removal efficiency of FCW was 31.1 ± 16.2%.

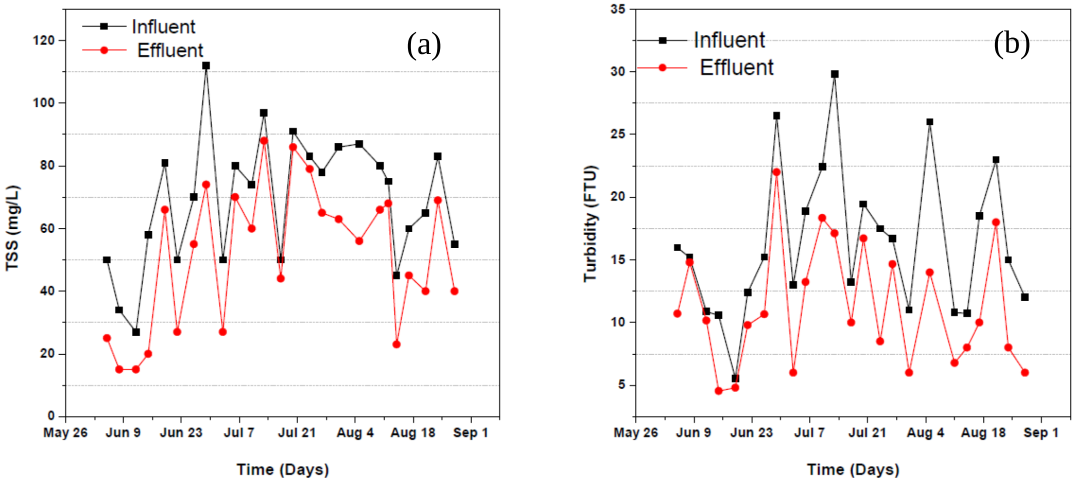


Figure 19: The variation of (a) TSS (b) Turbidity in FCW at the influent and effluent with time

Table 8: The percentage pollutant removal efficiency of FCW

Parameters	Efficiency (%)		
	Range	Average	S.D.
TSS	4.82 – 65.5	28.3	17.1
Turbidity	2.6 – 57.05	31.1	16.2
NO_3^-	42.7 – 84	61.5	11.7
NO_2^-	0 – 80	25.5	20.6
NH_4^+	21.5 – 45.6	32.9	6.5
PO_4^{3-}	25 – 70	52.9	12.5

Figure 20(a) shows the concentration of nitrate at the influent and effluent of FCW over time. During the study period, the concentration of NO_3^- in the influent and effluent ranged from 98 mg/L – 300 mg/L and 20 mg/L- 125 mg/L, respectively. The average nitrate removal efficiency was 61.5 ± 11.7% (Table 8). Due to the oxygenated environment, the nitrification process was not limited hence, ammonia and ammonium converted to nitrite and nitrate then floating plants uptake the available nitrate from the wastewater thus leading to effective removal of nitrate. The nitrate removal efficiency of 61.5 ± 11.7% in this study was higher than that obtained in a similar study by Weragoda *et al*. (2012) which was 40% nitrate removal efficiency for domestic wastewater treatment.

Nitrite concentration ranged between 0.3 mg/L – 0.9 mg/L and 0.2 mg/L – 0.7 mg/L at the influent and effluent, respectively (Fig. 20b). The average removal efficiency of 25.5 ± 20.6% was achieved (Table 8). Nitrite was removed in this stage through nitrification and physical attachment (Bu & Xu, 2013). The concentration of ammonium in the influent and effluent was in the range of 90 mg/L – 144 mg/L and 55 mg/L – 100 mg/L, respectively (Fig. 21a). Ammonium was removed at an average efficiency of 32.9 ± 6.5%. In this stage, ammonium was removed through the nitrification process, physical attachment and sedimentation.

Phosphate concentration at the influent was ranging from 15.8 mg/L to 48 mg/L and at the effluent; the range was 5.5 mg/L to 25 mg/L (Fig. 21b). The efficiency of FCW in removing phosphate was 52.9 ± 12.5% (Table 8). Phosphate was removed in this stage through adsorption, physical entrapment in the root zone, plant uptake, and bacteria uptake (Bu & Xu, 2013).

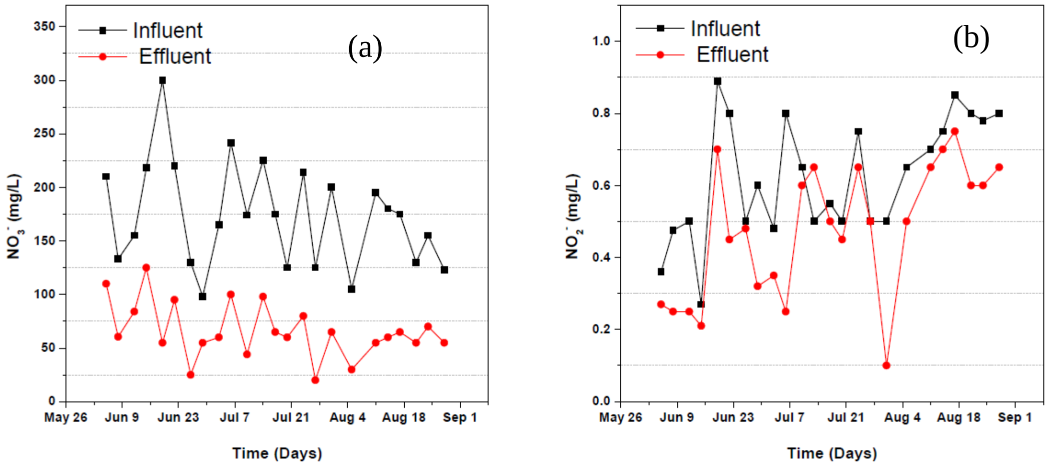


Figure 20: The variation of (a) NO_3^- (b) NO_2^- pollutants in FCW at the influent and effluent with time

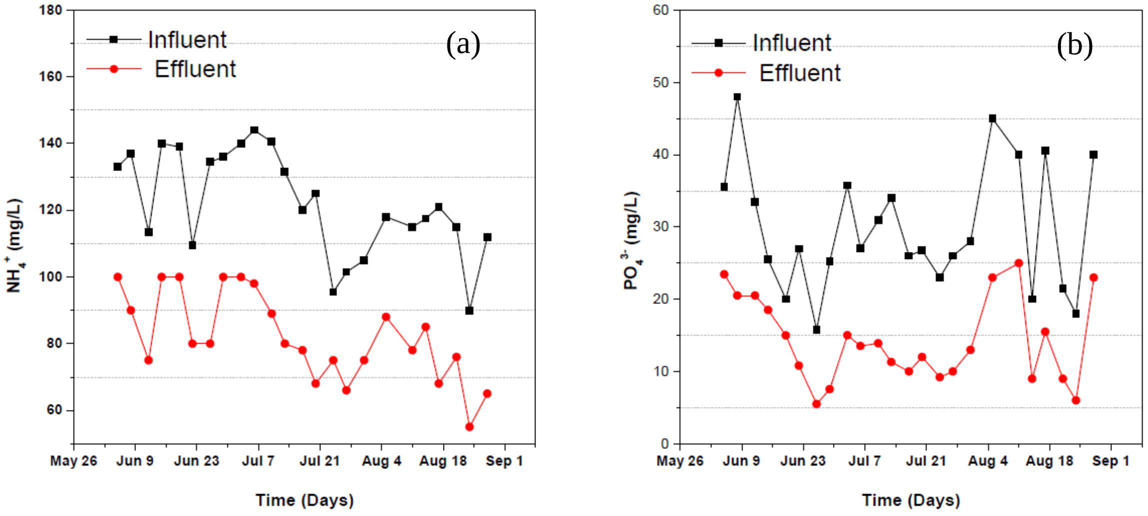


Figure 21: The variation of (a) NH_4^+ (b) PO_4^{3-} pollutants in FCW at the influent and effluent with time

4.2 Overall performance of the integrated treatment system

The concentration of TSS and turbidity at each treatment stage are presented in Fig. 22. The highest removal of TSS was observed at the ABR stage and FCW contributed low removal efficiency compared to the previous two stages. The average overall efficiency of the integrated system in removing TSS was 86.2 ± 6% (Fig. 23) and the final effluent from the integrated treatment system had an average concentration of 51.4 ± 23 mg/L that met the required standard for industrial effluent established by TBS (Table 9; TBS, 2009). The overall average removal efficiency of the integrated system in removing turbidity was 76.6 ± 9.5% (Fig. 23). Furthermore, the effluent from FCW had an average turbidity of 11.2 ± 4.8 FTU and it was below the maximum permissible limit of TBS for industrial effluent (Table 9; TBS, 2009).

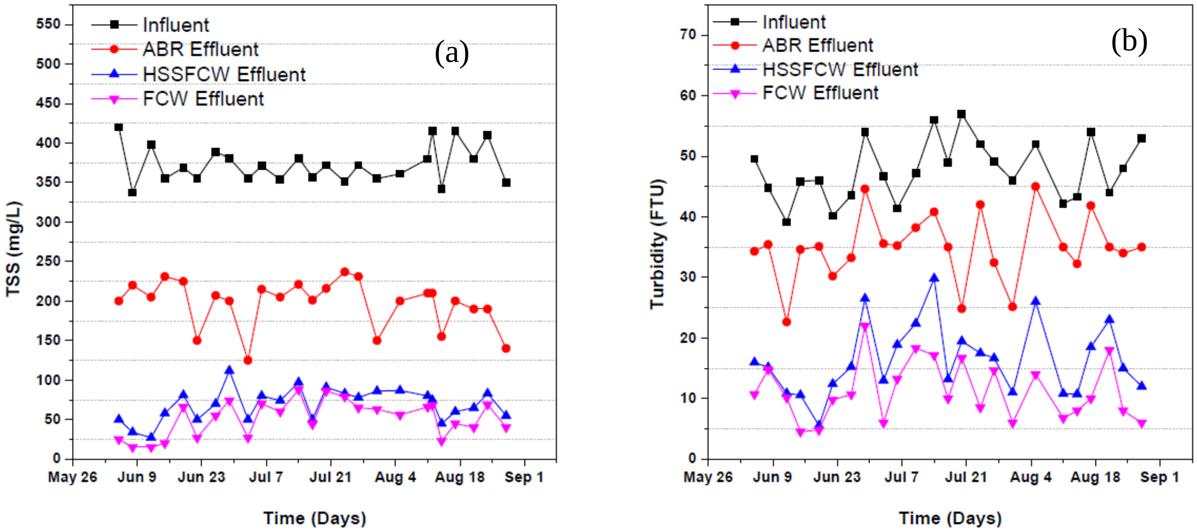
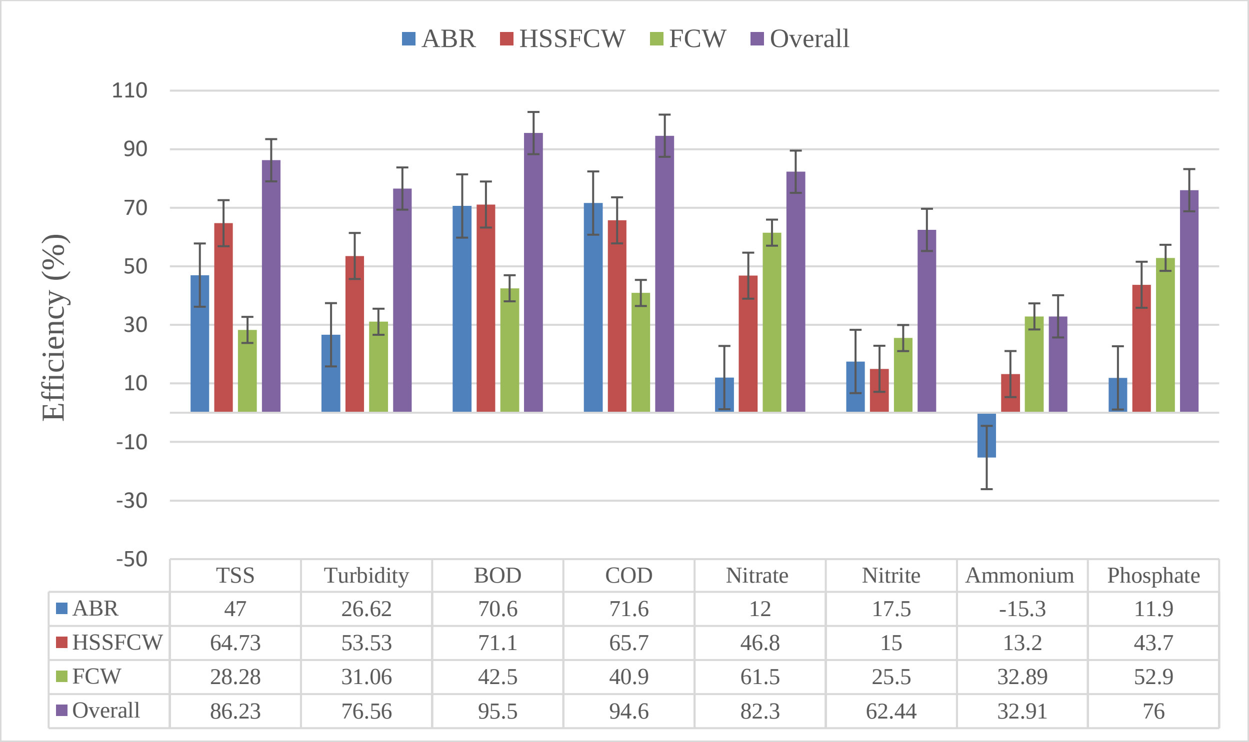


Figure 22: Pollutant concentration variation in each treatment unit with time (a) TSS (b) Turbidity



	TSS	Turbidity	BOD	COD	Nitrate	Nitrite	Ammonium	Phosphate
ABR	47	26.62	70.6	71.6	12	17.5	-15.3	11.9
HSSFCW	64.73	53.53	71.1	65.7	46.8	15	13.2	43.7
FCW	28.28	31.06	42.5	40.9	61.5	25.5	32.89	52.9
Overall	86.23	76.56	95.5	94.6	82.3	62.44	32.91	76

Figure 23: Average performance efficiency of the integrated system for various key parameters

Figure 24 shows the BOD_5 and COD removal performance of three treatment units. The overall average BOD_5 removal efficiency was 95.5 ± 1.9% (Fig. 23) and the average concentration of BOD_5 from FCW effluent was 26 ± 12.4 mg/L. Therefore, the final effluent from the integrated treatment system had a BOD_5 concentration which was below the permissible limit of 30 mg/L for industrial effluent (Table 9; TBS, 2009).

Average overall removal performance efficiency of 94.8 ± 4% was obtained for COD (Fig. 23) and the final effluent from the integrated system had an average concentration of 56 ± 39.9 mg/L which was below the allowable limit 60 mg/L for industrial effluent (Table 9; TBS, 2009). The BOD_5 and COD removal efficiency was higher when the wastewater passed through ABR and HSSFCW stages than the FCW. However, both stages (ABR and HSSFCW) demonstrated lower nitrogen removal efficiency compared to the FCW stage.

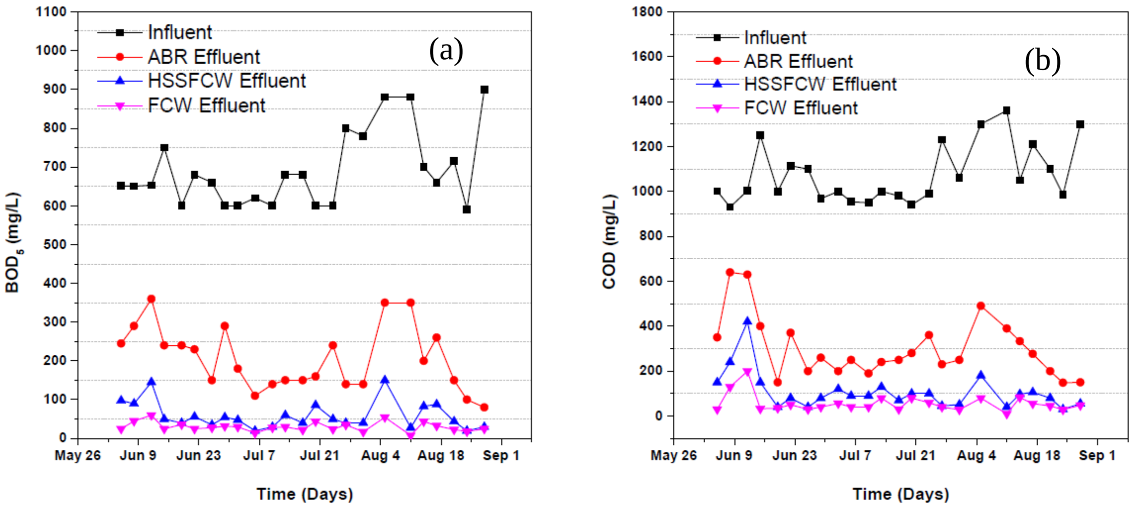


Figure 24: Pollutant concentration variation in each treatment unit with time (a) BOD_5 (b) COD

Figure 25 present the variation of nitrate and nitrite concentration across all treatment stages. The overall average efficiency of the integrated system was 82.4 ± 6% for the nitrate component (Fig. 23) and the average concentration of the NO_3^- in the effluent from FCW was 66.3 ± 25.8 mg/L, which was higher than the permissible limit of 20 mg/L for industrial effluent (Table 9; TBS, 2009). A high level of nitrate at the final effluent might be due to an elevated concentration of nitrate in the influent and low rate of denitrification in ABR and HSSFCW stage (Assefa *et al.*, 2019). A high level of nitrate with an average value of 376.9 mg/L was observed in the influent of ABR (Table 2). The reason for this high nitrate concentration was the industry discharges excess artificial fertilizers from the greenhouses to the wastewater reservoir. During the design of the integrated treatment system, the information on artificial fertilizer discharge was not given. Since ABR and HSSFCW were designed for major removal of organic matter, the size might not be adequate for the denitrification of nitrate. The denitrification process at the ABR and HSSFCW stage could be enhanced by adding supplementary carbon such as methanol, sugar, volatile fatty acid (Assefa *et al*., 2019).

The system was designed to combine HSSFCW and FCW for optimal removal of nutrients. A higher nitrification rate was observed at the final stage of the treatment compared to the previous stages because of the aerobic condition of the system. Nitrite was removed from the wastewater with an average efficiency of 62.4 ± 11.7%. The final effluent from the integrated treatment system had an average concentration of 0.4 ± 0.1 mg/L (Table 9).

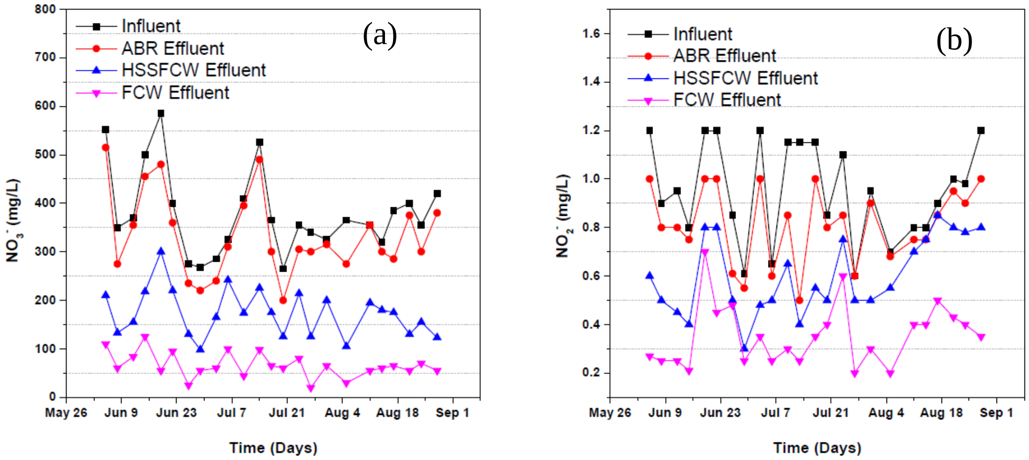


Figure 25: Pollutant concentration variation in each treatment unit with time (a) NO_3^- (b) NO_2^-

Table 9: Pollutant concentration at the inlet and outlet of the integrated system and national standard for industrial effluents

Parameters	Unit	Overall inlet	Overall outlet	TBS guideline values
pH	-	6.8 ± 0.3	7.5 ± 0.2	6.5 – 8.5
TDS	mg/L	962.2 ± 106.8	1001.8 ± 128.6	-
EC	µs/cm	1924 ± 213.5	2003.3 ± 256.63	-
Temperature	ºC	23.5 ± 1.6	21.8 ± 2.1	20 – 35
TSS	mg/L	373 ± 23.77	51.4 ± 23	100
Turbidity	FTU	47.7 ± 5	11.2 ± 4.8	300
BOD_5	mg/L	688.8 ± 95.7	26 ± 12.4	30
COD	mg/L	1074 ± 130.5	58.3 ± 39.7	60
NO_3^-	mg/L	376.9 ± 85.5	66.3 ± 25.8	20
NO_2^-	mg/L	0.9 ± 0.2	0.3 ± 0.1	-
NH_4^+	mg/L	123.6 ± 18.4	106.3 ± 18.7	-
PO_4^{3-}	mg/L	60.2 ± 11.5	14.2 ± 5.8	-

Figure 26 present the variation of ammonium and phosphate at each treatment stage during the study period. The overall average performance of 32.9 ± 13.1% was achieved for ammonium removal (Fig. 23). An increase of ammonium was observed at ABR this was because of the anoxic environment but later the level of ammonium decreased in HSSFCW and FCW due to the presence of oxygen in the systems. The reason for the low percentage of ammonium removal might be low rate of nitrification in HSSFCW and the high production of ammonium in ABR. It was observed that the concentration of ammonium in ABR was 123.6 mg/L and 141.5 mg/L for inflow and outflow, respectively. The production of ammonium in ABR likely to increase the level of ammonium in the effluent of the ABR system and decrease the efficiency.

The integrated system achieved an average removal efficiency of 76 ± 10.5% for phosphate (Fig. 23). The average concentration of phosphate in the final effluent was 14.2 ± 5.8 mg/L (Table 9). High removal of phosphate in the integrated system was contributed by HSSFCW and FCW.

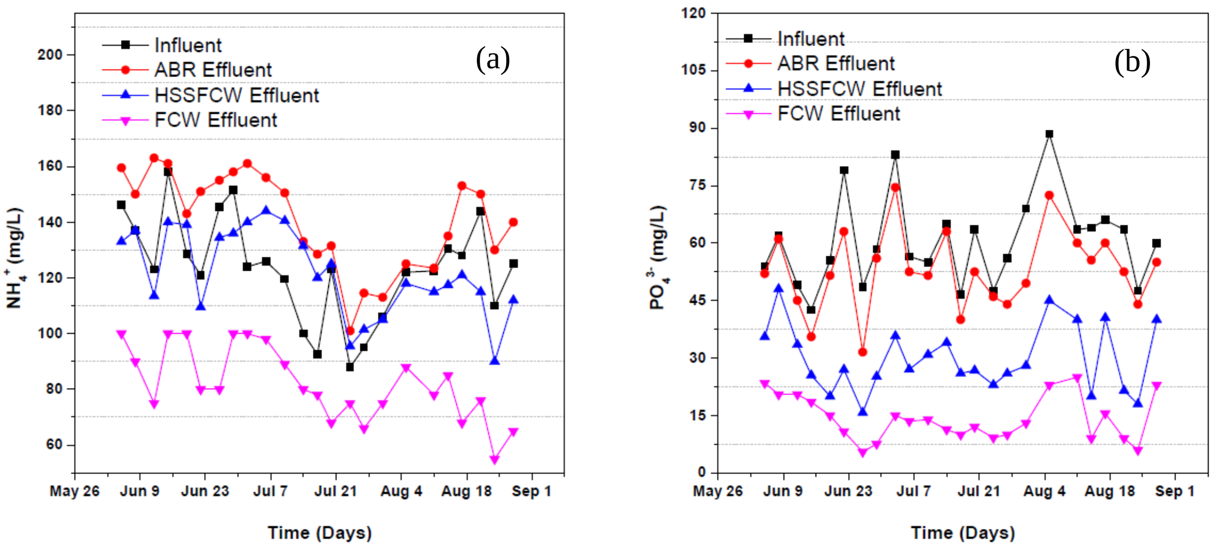


Figure 26: Pollutant concentration variation in each treatment unit with time (a) NH_4^+ (b) PO_4^{3-}

In this study, the overall performance of the integrated system in BOD_5 and COD removal was higher than the study done by EL-Khateeb *et al*. (2009) for the removal of pollutants using an integrated system composed of up-flow anaerobic sludge blanket reactor, free water surface constructed wetland, and subsurface flow constructed wetland. Furthermore, the present study showed a higher removal efficiency for TSS, BOD_5, COD, and phosphate than the one reported by Singh *et al*. (2009) on the performance of integrated systems composed of ABR, HSSFCW, and VFCW in treating high strong municipal wastewater.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Integrating different wastewater treatment technologies improve the effectiveness of pollutant removal from wastewater because each system is providing particular conditions for specific microbial and physical-chemical processes to take place. In this study, the performance of HSSFCW integrated with FCW and ABR in treating seed production wastewater was evaluated. The results obtained showed that the removal rate of TSS, turbidity, COD, BOD, nitrate, ammonium and phosphate was 86.23 ± 6%, 76.56 ± 9.52%, 94.6 ± 4%, 95.51 ± 1.9%, 82.3 ± 6%, 32.91 ± 13.07%, and 76.56 ± 10.5%, respectively.

The concentration of all pollutants except nitrate in the effluent from the last treatment stage were below the permissible limit for industrial effluent. A high concentration of nitrate at effluent was because of the large input of nitrate at the influent. The industry was discharging its excess artificial fertilizer from their greenhouse to the wastewater reservoir. During the designing of the integrated system, the information on the excess artificial fertilize discharge was not provided. According to the results obtained, the use of integrated treatment series containing ABR followed by HSSFCW and FCW is a promising technology for pollutant removal from seed production wastewater and the treated wastewater was potential for use in irrigation activities.

5.2 Recommendations

For seed production industrial wastewater with artificial fertilizer discharge to effectively remove the nitrate and to meet the national standard for industrial effluent, HSSFCW should be sized for nitrate removal through denitrification process because sizing using BOD was not good enough due to the large input of nitrate. Moreover, for the existing system at Enza Zaden, another post-treatment should be provided such as HSSFCW. This will let the nitrate to be removed through denitrification process, plant uptake, sedimentation, adsorption, and plant root attachment.

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RESEARCH OUTPUTS

(i) Research paper accepted in Water Practice and Technology Journal

(ii) Poster presentation