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Removal efficiency of organic matter and pathogens for horizontal flow subsurface constructed wetlands treating domestic wastewater in Kigali.

A dissertation submitted to the Department of Chemistry, School of Science, College of Science and Technology, University of Rwanda, in partial fulfillment of the requirements for the Degree of Masters of Science in Environmental Chemistry.

By

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Kigali, August 2024

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I, Cyriaque NGOBOKA, hereby declare that this master dissertation titled “**Removal efficiency of organic matter and pathogens for horizontal flow subsurface constructed wetlands treating domestic wastewater in Kigali**” is my own original work. It is submitted at the University of Rwanda for partial fulfillment for the award of the Degree of Masters in Environmental Chemistry of the University of Rwanda. This dissertation has never been submitted and will not be submitted elsewhere for any other award of the degree or academic certificate.

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DEDICATION

To

God almighty; he who makes all things possible,

My parents who gave me life,

My beloved wife Chancelline TUYAMBAZE, my daughter and my son,

And other members of my family,

All other individuals who assisted me during my research.

This work is mercifully dedicated.

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ABSTRACT

Now days the world is facing a big problem of getting sufficient quality water. This is due to the increase of the world population and industrialization as well as climate change which are affecting water resources due to the discharge of untreated wastewater and causes an impact on the environment and public health mainly in developing countries such as Rwanda. Constructed wetlands (CWs) utilization can provide sustainable domestic wastewater treatment because they rely on natural processes, less expensive to build, operate and maintain, low or no energy usage, no chemical consumption, provide habitat for wildlife and organisms and eco-friendly compared with conventional wastewater-treatment systems and the purified water with CWs can be suitable for reuse in irrigation and harvested plants can have economic value. In Rwanda there is few CWs for treating wastewater but there are no appropriate management mechanisms for those treatment systems in order to keep them in a sustainable manner. Therefore, the main objective of this study was to evaluate the removal efficiency of organic matter and pathogens of local full scale horizontal sub-surface flow constructed wetlands at Excella School in Kigali. During the monitoring period of 6 months, the average removal efficiencies of analysed pollutants parameters of the effluent were: COD (56.8 %), BOD₅ (54.9 %), TN (46 %), TP (47.9 %), TC (94.58 %), FC (95.60 %) and *E. coli* (98.89 %). The average Biodegradability Index of the effluent was 0.78. Pollutants removal efficiency was increased as the macrophytes grew and the effluent from the studied constructed wetlands didn't meet the standards of water for irrigation. Generally, the removal efficiencies of the pollutants were not high due to the fact that the wetlands macrophytes were still growing and macrophytes are the main in pollutants removal. Also effluent parameters such as pH, Temperature, Electric conductivity, TDS and TSS were analysed and they met the standards of the domestic wastewater to be released in the environment. The results showed that the pathogens were highly removed but the effluent did not comply the standards as well as BOD₅ while TN, TP and COD comply with the standards. Inspecting the effluent quality regularly, introducing new microorganisms into CWs, further research, planting other macrophytes, trained staffs to be in charge of the CWs monitoring, operation and maintenance are recommended.

Keywords: Domestic wastewater, Constructed wetlands, nutrients, organic matter, pathogens, biodegradability index and irrigation.

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ACRONYMS AND ABBREVIATIONS

BOD₅: Five-day Biochemical Oxygen Demand

COD: Chemical Oxygen Demand

CWs: Constructed Wetlands

SF: Surface Flow

SSF: Subsurface Flow

EPA: (US) Environmental Protection Agency

SDG: Sustainable Development Goal

HSSFCWs: Horizontal Subsurface Flow Constructed Wetlands

pH: Hydrogen Potential

RPHC: Rwanda Population and Housing Census

RS: Rwanda Standards

SSFCWs: Subsurface Flow Constructed Wetlands

TSS: Total Suspended Solids

U.S.A: United States of America

UV-vis: Ultra-Violet visible

WWTP: Wastewater Treatment Plant

TN: Total nitrogen

RE: Removal Efficiency

TP: Total Phosphorus

FC: Faecal Coliforms

TC: Total coliforms

E-coli: *Escherichia Coli*

CHAPTER 1: GENERAL INTRODUCTION

1.1 Background

Now days, the world is facing a big problem of getting sufficient quality water[1]. This is due to the increase of the world population and industrialization as well as climate change is affecting water resources, which are mainly stressed in developing countries such as Rwanda. Rwanda is landlocked country with high population density of 503 inhabitants per Km² in 2022 and is projected to be 759 inhabitants per Km² in 2042[2]. This increasing rate of populations needs to protect the existing water sources by implementing the wastewater treatment systems and increasing sanitation facilities.

According to the Fifth Integrated Household Living Conditions Survey (EICV5) in Rwanda, only 87% of the population has access to improved drinking water sources [3] and the average water consumption is roughly 20 L/capita/day [4]. Additionally, 84.3% of the population uses pit latrines with solid slabs, 9.8% uses pit latrines without slabs, and only 1.9% uses flush toilets. The majority of the time, property owners manage wastewater on-site using septic tanks and soak pits, but schools and other institutions of a similar size generate large volumes of wastewater that are difficult to manage with soak pits and septic tanks. Instead, they may reuse the wastewater in agriculture due to its fertilizing qualities, or they may discharge it untreated into bushes, rivers, or natural wetlands, though it may contain contaminants above the permissible limits.

There are about 161 wastewater treatment systems in Rwanda, with most of the systems concentrated in the city of Kigali [5]. These are small, often on-site treatment systems and several of them present environmental or public health concerns to the respective region. To tackle the issue of untreated wastewater, the government of Rwanda has opened a tender in 2017 for a project of building its first Kigali central wastewater treatment plant in Nyarugenge District with the capacity of 120,000 populations equivalent, i.e. approximately 10% of the population in Kigali City and it is scheduled to be ready in 2024 [6].

By considering the lack of adequate centralised wastewater systems, it should be noted that the current government effort needs to be supported by other sustainable and economical solutions of wastewater treatment systems which also consider the wastewater valorisation and simple, but effective, operation methods by local communities. For such systems, CWs are considered as a prime candidate using sustainable solutions, especially for small communities [7] . In fact, considering their low cost, easy operation and maintenance as well as their use of natural process, CWs have been reported by different authors (like Tang[8] and Gomes [9]) as proven sustainable natural wastewater treatment systems with high potential for application in developing countries.

The use of on-site systems including constructed wetlands has started to emerge slowly in this decade in Rwanda. The horizontal sub-surface flow constructed wetlands are preferred mainly in local schools, large institutions and small communities and this was pushed by the government enforcement of the 2005 organic law of the environment and its subsequent Law N°48/2018 on the environment. The currently known systems/institutions that has constructed wetlands as part of their components include Kinigi model village, the Nyarutarama wastewater ponds, Gashora Girls Academy, Excella School, Kigali Parents School, Mageragere Prison, the University of Lay Adventists of Kigali and Gishari Integrated Polytechnic. In addition, considering their low cost, easy operation and maintenance, CWs will likely be used in the planned green model villages and or in the cities in Rwanda.

Wastewater treatment in urban areas is one of the major concerns [10]. Conventional wastewater treatment systems are applied in many countries for treating wastewater. However, considering cost, contaminant removal efficiency, and operational skills required for conventional wastewater treatment, natural wastewater treatment systems are considered as more appropriate for developing countries where land is available [1]. Natural wetlands were historically used as wastewater discharge sites. A natural wetland is still used for wastewater treatment under controlled conditions and the use of constructed wetlands has increased significantly to improve water quality by using different natural processes with high potential for application in developing countries [11]–[13].

At the Max Plank Institute, Seidel initiated the deliberate creation and research of wetlands to remediate wastewater in 1952. Because of the simplicity of the systems in terms of mechanical operation, biological complexity, and high level of treatment, research in this area has advanced since 1985. The ability to complete construction using local resources and labor is another appealing benefit for developing nations [10]. Wastewater treatment in constructed wetlands (CWs) has a lot of potential. These systems are made up of helophyte, beds or channels that use physical, chemical, and biological processes to purge toxins from wastewater [14]. Surface flow (SF) and subsurface flow (SSF) are the two main categories for CWs. Vertical flow wetlands extend back to Seidel's time, but the first full-scale horizontal flow artificial wetland was built and operated in the Netherlands in 1975 [10].

Both SFCWs and SSFCWs are capable of eliminating pathogens, total suspended solids, nitrogen, phosphorus, biochemical oxygen demand, and chemical oxygen demand from various home and industrial wastewater types [15]. Several mechanisms including both aerobic and anaerobic microbiological conversions, sedimentation, mineralization, chemical transformations, physicochemical adsorption, chemical precipitation and ion exchange are involved for contaminants removal from wastewaters in the root zone of constructed wetlands [14],[15].

This technology act as a natural and low-cost treatment facility for wastewaters of different origin. The wetland design, hydraulic loading rate, type of contaminant, microbiological interactions, and climatic conditions are the key determinants of the treatment efficacy of CWs. These systems require a low hydraulic loading rate and a long hydraulic retention time for the optimal treatment efficiency [14]. Domestic wastewater, acidic mine drainage, agricultural wastewaters, landfill leachate, urban storm-water, and industrial wastewater including paper and pulp, food processing, petrochemical industry, chemical, tannery [10], [16], and textile [10], [17] are all treated using CWs.

Wastewater treatment should be viewed as a component of ecological principles, Sustainable Development Goals (SDG), which emphasise that the world needs to improve water and sanitation-related services and the management of water resources, and technological interventions were required to enhance wastewater treatment. It is necessary, in particular, to address the issue of the scarcity of available land in urban areas.

Recently, the use of CWs as an ecological system for wastewater treatment has become increasingly popular in the world, especially in the areas without public sewage systems and economically in developing countries [1]. Along with the consideration of inexpensive and effective ecological wastewater purification techniques, CWs have been successfully used to remove a diverse array of pollutants originating from almost every conceivable contamination source [15]. In this study, we evaluated efficiency removal of certain pollutants for local full scale Horizontal Subsurface Flow Constructed Wetlands (HSSFCWs) treating domestic wastewater in Kigali at Excella School where findings can be used in CWs improvement.

1.2 Problem statement

The discharging of untreated or partially treated domestic wastewater causes an impact on the environment and public health is often due to the lack of centralized WWTP and knowledge in conventional wastewater treatment methods and related high cost especially in low and middle income countries [19], [20]. This result in the contaminated downstream water supplies becoming unfit for drinking, irrigation and recreational activities [10], due to the presence of nutrients, toxic heavy metals, toxic organic pollutants and pathogens. Untreated wastewaters discharged into the freshwater bodies change the quality of freshwater [10]. Besides deteriorating the freshwater bodies, it causes eutrophication, the farmland soil and farmland resources characteristics are also changed due to the use of contaminated river waters or direct use of wastewater for irrigation [19].

Pathogens found in domestic wastewater cause water borne and excreta related diseases such as diarrhea, *Escherichia histolytica*, *Escherichia coli* and ascariasis which accounted for nearly two thirds of all the neglected tropical diseases (around 737,000 cases) in 2012. [19], [21] reported this outbreaks of waterborne diseases also in Ethiopia. Constructed wetlands utilization can provide sustainable domestic wastewater treatment [9], because they rely on natural processes, less expensive to build, operate and maintain, low or no energy usage, no chemical consumption, provide habitat for wildlife and organisms and eco-friendly compared with conventional wastewater-treatment systems [8],[9],[22]–[24]. The purified water with CWs can be suitable for reuse in irrigation and harvested plants can have economic value[20] .

The use of this technology is unfortunately still limited in developing countries because of poor understanding of the potential of constructed wetland, under searched and implemented [25]. This is caused by a lack of information on constructed wetland performance, that is why we have chosen to evaluate efficiency removal of organic matters and pathogens for local full scale HSSFCWs treating domestic wastewater in Kigali at Excella School for better understanding which can improve the utility of CWs in Rwanda. It is crucial for a highly populated, and developing nations like Rwanda with water scarcity, to treat the domestic wastewater with CWs before its discharge or reuse in order to reduce human and ecological contamination, while reducing the stress on the available freshwater for sustainable development.

1.3 Objectives of the study

1.3.1 General objective of the study

The general objective was to evaluate the removal efficiency of organic matter and pathogens of local full scale horizontal sub-surface flow constructed wetlands in Kigali.

1.3.2 Specific objectives of the study

The specific objectives of the study were:

- i. To evaluate organic matter, nutrients and pathogens removal efficiency of local full scale horizontal subsurface flow constructed wetlands treating domestic wastewater at Excella School in Kigali.
- ii. To determine biodegradability index of the effluent from local horizontal subsurface flow constructed wetlands treating domestic wastewater at Excella School in Kigali.
- iii. To compare the effluent from local full scale HSSF constructed wetlands treating domestic wastewater at Excella School in Kigali with the standards of water for irrigation.

1.4 Research questions

By taking into consideration the attainment of the above-mentioned objectives of the study, the following research questions were focused on during the study:

- i. What is the efficiency removal of organic matter, pathogens and nutrients in the local full scale HSSF constructed wetlands of Excella School?
- ii. What is the biodegradability index of the effluent from local full scale HSSF constructed wetlands treating domestic wastewater at Excella School in Kigali?
- iii. How is the suitability of effluent to be reused for irrigation, based on the standards of water of irrigation?

1.5 Significance of the study

The significance of this study mainly will contribute in minimizing water pollution in Rwanda. In particular, this research will help the global achievement of Sustainable Development Goal (SDG) number 6 to ensure availability and sustainable management of water and sanitation for all but is in other ways related to several other SDGs, such as SDG2 Zero Hunger (~ wastewater reuse in agriculture) and SDG13 Climate (~ reduce energy need for wastewater treatment) [18] .

In Rwandan context, where various feasibility studies are currently initiated for building and upgrading wastewater treatment plants, this research can play a key role in realizing different cost saving opportunities and environmental benefits such as cheap wastewater treatment and wastewater reuse. CWs are and will be used in the schools, hospitals, universities, planned green model villages and or in the cities in Rwanda. Therefore, the research output will be used for improving CWs treating wastewater in Rwanda.

In addition, Rwanda has developed in 2011 a green growth and climate resilience strategy as a long-term vision 2050 which include wastewater recycling and integrated soil fertility management in a number of immediate programs that can be implemented to fully implement the strategy. To achieve the intended development and growth until 2050, the research institutions in Rwanda will play a leading role in the frame of three pillars of research, education, and community outreach.

CHAPTER 2: LITERATURE REVIEW

2.1 Definition of domestic wastewater and its sources

All contaminated water from homes, businesses, restaurants, hospitals, and other facilities is referred to as wastewater [26]. It also comprises agricultural, horticultural, and aquaculture water residues, as well as storm water and urban runoff. There are three classifications for it: black water, grey water, and yellow water [26]. Water is unsafe for various uses, such as drinking and cooking, as a result of the introduction of specific contaminants [26].

We concentrate on domestic wastewater in this review. Domestic wastewater is the kind of waste that is typically discharged from or is comparable to that discharged from plumbing fixtures, appliances, and other household gadgets, such as but not limited to toilets, bathtubs, showers, laundry facilities, dishwashing facilities, and garbage disposals. Domestic wastewater can come from industrial facilities where it is separated from industrial wastewater, as well as from commercial structures like office buildings, retail stores, and some restaurants [26], [27]. Industrial wastewater is not included in domestic wastewater. Some domestic wastewater sources are depicted in figure 1.



Figure 1: Source of domestic wastewater [27], [26]

Domestic wastewater is divided into three categories such as black water, grey water and yellow water as it is defined in table 1 which is below.

Table 1: Categories of domestic wastewater [27]

Yellow water	Human urine
Brown water	Human faeces with flushed water (can include paper if used)
Black water	Human faeces (brown water) mixed with urine (yellow water), in general: wastewater from toilets. It contains human waste and can be a public health if not treated properly. (Sometimes, water used in kitchen is also classified as black water.
Grey water	Water used in kitchen, bathroom including sinks, baths, showers and laundry, etc. or any water that has been used at home, except water from toilet.

2.2 Domestic wastewater characteristics

Domestic wastewater has a particles concentration of roughly 0.1% and is 99.9% water, according to the research by Özoguz [27]. By Physical characteristics, domestic wastewater is usually characterised by a grey colour and often smells musty. A mixture of excrement, food scraps, toilet paper, grease, oil, soap, salts, metals, detergents, sand, and grit make up the solid substance and both suspended (approximately 30%) and dissolved (about 70%) materials are possible. Chemical and biological processes both have the potential to precipitate dissolved materials. When discharged into the receiving Environment, suspended particles have the potential to create anaerobic conditions and sludge deposits from a physical standpoint [27].

By Chemical characteristics, domestic wastewater is mostly made up of organic (70%) and inorganic (30%) components, as well as a variety of gases. Carbohydrates (25%) and proteins (65%) make up the majority of organic molecules, reflecting the human diet [27]. Heavy metals, nitrogen, phosphorus, pH, sulphur, chlorides, alkalinity, hazardous substances, etc. are examples of inorganic components [27]. But since wastewater contains more dissolved solids than suspended solids, between 85 and 90 percent of the total inorganic component and between 55 and 60 percent of the total organic component are dissolved. Gases such hydrogen sulphide, methane, ammonia, oxygen, carbon dioxide, and nitrogen are frequently dissolved in wastewater. The first 3 gases are produced as a result of organic stuff in the wastewater decomposing [27].

Domestic wastewater comprises a variety of microorganisms according to biological features, but the ones that are of concern are those categorised as Protista, plants, and animals [27]. Algae, protozoa, fungi, and bacteria all fall under the Protista classification. Ferns, mosses, seed plants, and liverworts are all examples of plants [27]. Animals fall within the group of both invertebrates and vertebrates. The Protista category, particularly the bacteria, algae, and protozoa, is crucial for wastewater treatment [27]. Additionally, wastewater is home to a variety of harmful organisms, most of which are derived from sick or disease-carrying humans. Faecal coliform concentrations in raw wastewater range from a few hundred thousand to tens of millions per 100 ml of sample [27].

Domestic wastewater's strength and composition vary hourly, daily, and seasonally, with the average strength depending on factors including per capita water usage, habitual water use, nutrition, living standards, and life style [27]. The main cause is the difference in home water usage. Compared to households in underdeveloped nations, households in developed nations consume. Domestic wastewater components can be divided into different main groups as shown in Table 2. Untreated domestic wastewater can adversely affect the aquatic life if they are discharged into the environment [27].

Table 2: Domestic wastewater components and their environmental impacts [27]

Component	Of special interest	Health and ecological risks
Microorganisms	Pathogenic bacteria, virus and worms eggs	Risk when bathing and eating shellfish and can lead to transmission of pathogenic diseases
Biodegradable organic materials	Oxygen depletion in rivers and lakes	Fish death, odours, can lead to the depletion of natural oxygen in aquatic environment.
Nutrients	Nitrogen, phosphorus, ammonium	Eutrophication, oxygen depletion, toxic effect, ground water contamination.
Odour (and taste)	Hydrogen sulphide	Aesthetic inconveniences, toxic effect

The sized institutions such as schools and universities as well as different estates and modern city villages produce high volume of municipal wastewater which is difficult to treat with septic tanks, although it may be discharge into environment untreated with contaminant levels exceeding the tolerant limits for domestic wastewater discharge as mentioned in Rwanda Standards, RS 110:2017 of Rwanda Standard Board [28].The physical, chemical and microbiological contaminants tolerance limits for municipal wastewater discharge are summarised in the Table 3.

Table 3: Rwanda Standard Board tolerable limits for wastewater discharge [28].

Parameters	Limits
TDS, mg/L	≤1500
TSS, mg/L	≤50
pH	5-9
N (total), mg/L	≤30
P (total), mg/L	≤5
BOD, mg/L	≤50
COD, mg/L	≤250
Coli forms, No./100mL	≤400

2.3 What are wetlands?

Wetlands are regions where land and water meet. Therefore, the distinction between wetlands and uplands or deep water is not always clear. The name "wetlands" refers to a variety of wet ecosystems, such as floodplains, tidal wetlands, marshes, bogs, swamps, wet meadows, and ribbon (riparian) wetlands along stream channels [29], [30]. The presence of surface or near-surface water, at least occasionally, is a feature shared by all wetlands, whether they are natural or artificial, freshwater or saltwater [30]. Most wetlands have hydrologic circumstances where the substrate is soaked for long enough during the growing season to deplete it of oxygen [30]. Wetlands typically have slow flows, shallow waters, or saturated substrates as their hydrology. As water moves through the marsh, sediments might settle due to the slow flows and shallow water depths. Longer contact durations between the water and the surfaces within the wetland are also made possible by the sluggish flows [30].

A broad community of microorganisms that degrade or transform a wide range of chemicals is fostered by the complex mass of organic and inorganic components and the varied opportunities for gas/water interchanges. A dense growth of vascular plants suited to saturated conditions can be seen in the majority of wetlands. This vegetation slows the flow of water, generates microenvironments inside the water column, and offers microbial communities places to attach. As plants die back in the fall, litter builds up, creating more material and exchange sites as well as a source of carbon, nitrogen, and phosphorus to feed microbial processes [30].

2.4 Wetland functions and values

Wetland values are characteristics of wetlands that society considers to be advantageous. Wetland functions are the natural processes that occur in wetlands. While not all wetlands offer all functions and values, the majority of wetlands do under the proper conditions. Wetlands can be used for a variety of purposes, including the improvement of water quality, flood storage, the desynchronization of surface runoff and storm rainfall, the cycling of nutrients and other materials, habitat for fish and wildlife, passive recreation like bird watching and photography, active recreation like hunting, education and research, and aesthetic and landscape enhancement benefits [30, 31].

Where landforms channel surface water into shallow basins and where a somewhat impermeable subsurface layer prevents the surface water from penetrating the earth, wetland formation is likely to occur. A wetland can be built under these circumstances. By sculpting the land surface to collect surface water and sealing the basin to keep the water, a wetland can be created practically any place in the terrain [30].

2.4 Constructed Wetland

A constructed wetland is a man-made wetland that is intended to resemble a natural wetland. It is a shallow basin that is filled with some kind of substrate, typically soil or gravel, and is planted with vegetation that can withstand being soaked with water [30], [31]. Water is brought into the wetland at one end and flows over the top or through the substrate before being released at the other end through a weir or other structure that regulates the water depth [30].

The following five elements make up a constructed wetland: a basin, a substrate, vegetation, a liner, and an inlet and outlet arrangement system [31]. Constructed wetlands are artificial structures created to use the microbial population, soils, and plants of wetlands to treat wastewater in a controlled manner [32]. The alternative method for wastewater treatment in developing nations is constructed wetlands, although adoption rates are low due to the lack of technical capability and awareness [33].

Constructed wetlands can be classified based on the flow regime or the type of the plants as shown in Figure 2 below. The flow regime can be classified into Surface Flow (SF) and Subsurface Flow (SSF) constructed wetlands discussed in the following sections [19].

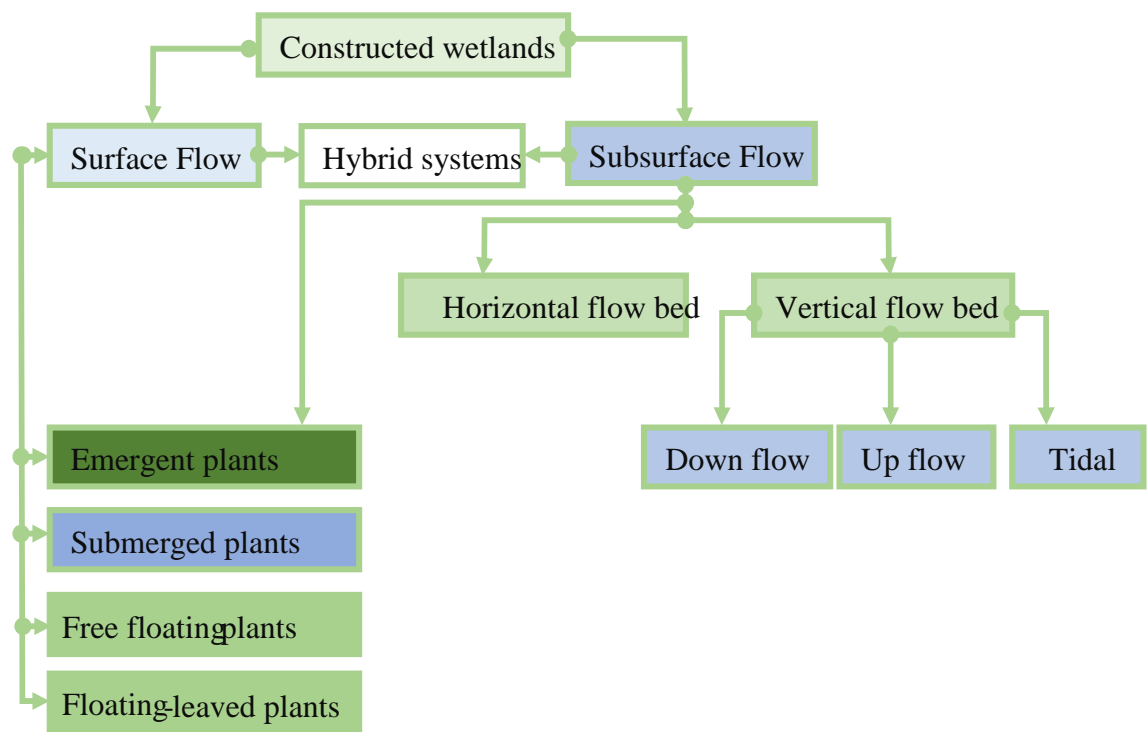


Figure 2: Classification of constructed wetlands [19]

2.4.1 Surface flow constructed wetlands

Surface flow constructed wetlands (surface flow CWs) are made up of surface water that is exposed to the atmosphere (20-40 cm deep) and frequently contains 20-30 cm of rooting soils, and the intended flow path through the system is horizontal (Figure 3 below) [34]. Surface flow CWs offer greater water flow control, and their water budget can be calculated using the Equation 1 [35].

$$\frac{dv}{dt} = Q_i - Q_o + Q_c - Q_b + Q_{sm} + (P - ET - I)A \quad (1)$$

Where Q_i = influent wastewater flow (m^3/s); Q_o = effluent wastewater flow (m^3/s);

P = precipitation (m^3/s); ET = evapotranspiration (m^3/s); V = volume of water (m^3); t = time (s);

dv/dt = rate of change in water volume (m^3/s); Q_{sm} = snowmelt (m^3/s); I = infiltration to ground (m^3/s); Q_c = catchment runoff rate (m^3/s); Q_b = bank loss rate (m^3/s), A = wetland top surface area (m^2).

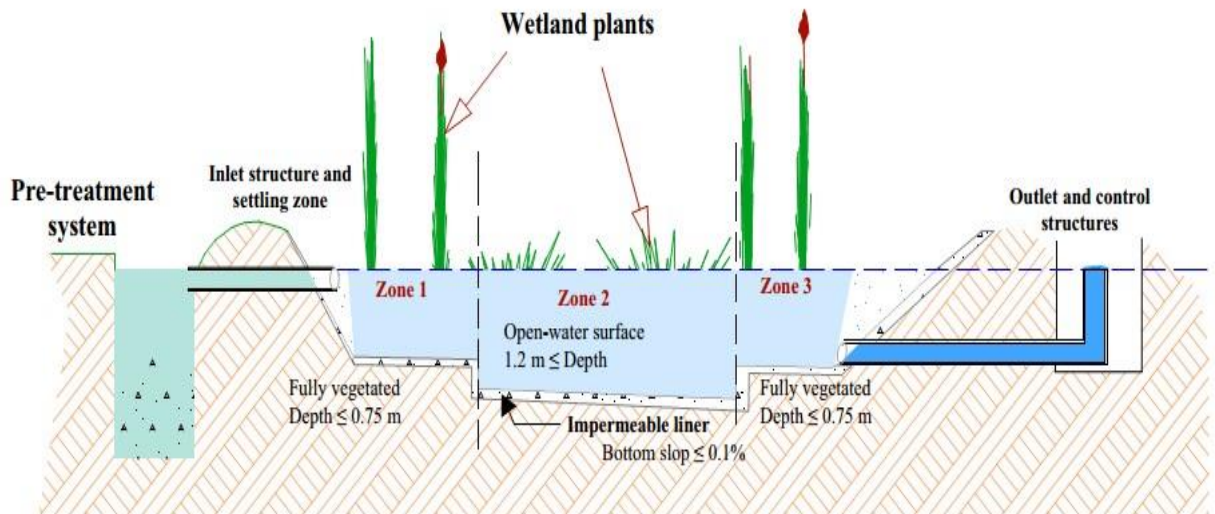


Figure 3: A typical section of a surface flow constructed wetland [35]

2.4.2 Subsurface flow constructed wetlands

SSF constructed wetlands are made up of a sealed basin and a porous rock or gravel substrate. It is intended for the water level to remain completely below the surface. Vegetated submerged bed, root zone method, microbial rock reed filter, and plant-rock filter systems are some of the other names for SSF systems. They are even walkable and don't have the mosquito issues that surface flow CWs do [35]. Subsurface constructed wetland can be divided into horizontal flow bed or vegetated submerged bed CWs (figure 5) and vertical flow bed CWs (figure 4) depending on the direction of the flow [36].

The vertical flow bed constructed wetlands are far more aerobic and need less area than the horizontal flow constructed wetlands, which generally have limited oxygen transfer [34]. Due to their greater operational requirements and requirement to pump wastewater onto the wetland surface, vertical flow bed CWs have not been as widely used as other CW types [34].

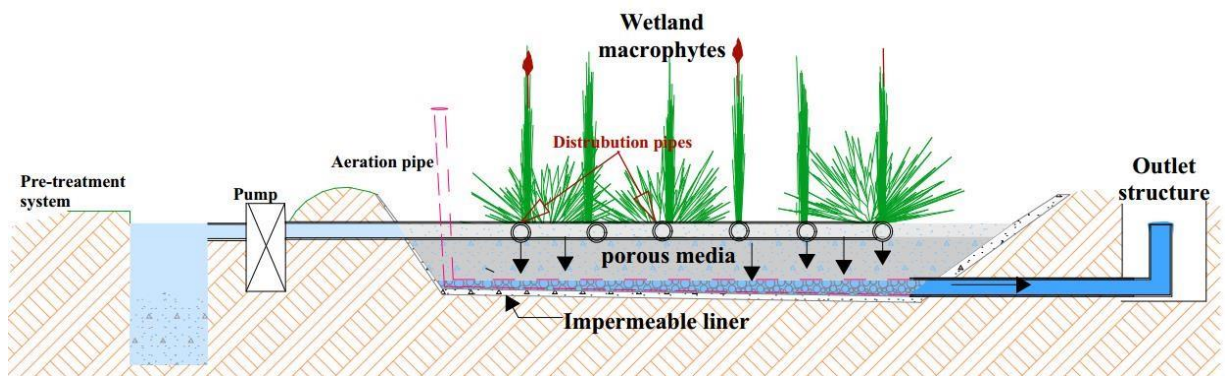


Figure 4: A typical section of a vertical flow bed constructed wetland

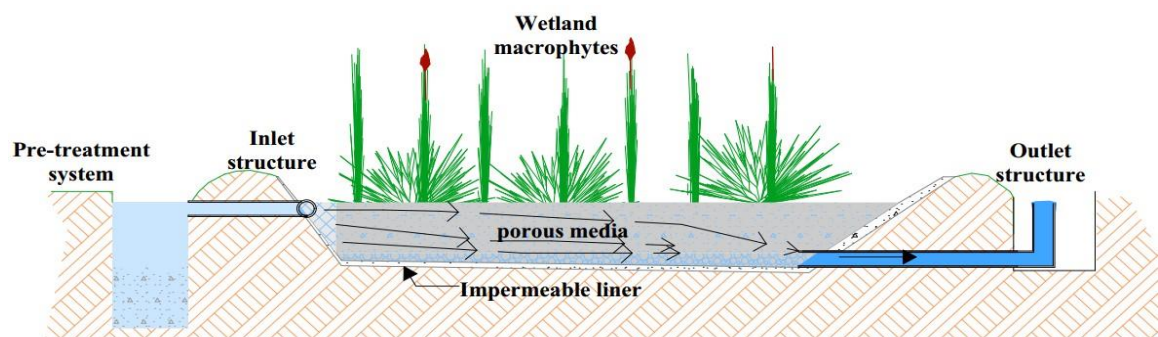


Figure 5: A typical section of a horizontal flow bed constructed wetland

Regardless of the kind of CW employed, constructed wetland treatment involves the pre-treatment of wastewater (primary treatment) in order to maximise performance and decrease the necessary surface area [37]. Depending on the wastewater sources, different levels of pre-treatment may be necessary for black water versus greywater. In order to take advantage of each system's unique characteristics, one or more types of artificial wetlands can be merged to create a hybrid system, as shown in table 4 below.

Table 4: Advantages and disadvantages of different types of constructed wetlands [19]

CW types	Advantages	Disadvantages
Surface flow	High removal rates of pathogens, Aesthetics, and wildlife habitat.	Large area, breeding ground for vectors, odor problems, high water loss, exposure to surface wastewater.
Horizontal flow bed	High denitrification, low costs, small area, low odor and vectors.	Clogging problems, lower pathogenic and nutrient removal rate.
Vertical flow bed	High nitrification, smaller area, low odor and vectors.	Expertise and pumps requirement, high capital cost and maintenance. Low pathogenic and nutrient removal rate.

2.4.3 Constructed wetlands components

A well-designed basin with water, a substrate, and most frequently vascular plants makes up a manmade wetland [16]. A wetland can be built by adjusting these elements. Communities of microorganisms and aquatic invertebrates, which are also significant wetlands components, develop naturally [30].

2.4.4 Constructed wetland substrates, litter and sediments

Constructed wetland substrates, litter (primarily fallen plant material), and sediments filter and trap particles, act as a medium for plant and microbial growth, store contaminants, and make it easier to distribute wastewater through the depth of the bed. Chemical and biological transformations take place within the substrates [38]. As a result of their accessibility and generally lower cost, the substrates are typically soil, organic materials like compost, sand, gravel, or crushed stone.

Due to the low water velocity and high productivity typical of wetlands, sediment and litter collect in the wetland. Due to their coarseness, these substrates are not especially good at removing phosphorus, but other substrates such as clay aggregates and steel slag have been discovered to be successful in doing so [39]. Safety factors should be added to the media hydraulic conductivity [36] in order to lower the potential clogging hazards over time, and the substrates in the inlet zone should be examined frequently or changed as necessary.

Table 5: Hydraulic conductivity values of substrate materials often available in Rwanda [19]

Substrate	Hydraulic conductivity (clean), m/d
5-10 mm gravel	34 000
14 mm fine gravel	15 0000
22 mm coarse gravel	64 000
19 mm rock	120 000

2.4.5 Constructed wetland vegetation

In manmade wetlands, both vascular plants (the higher plants) and non-vascular plants (algae) are essential. 4-6 plants are typically planted per square meter in constructed wetland vegetation, which can be divided into emergent, submerged, and floating plants [34]. Emergent vegetation, or non-woody plants that grow with their roots in the substrate and their leaves and stems emerging from the water surface, is typically placed in constructed wetlands. Native species are often advised since they are more able to survive wet circumstances, loading into the system, substrate type, and local climate [30].

Algae photosynthesis raises the water's dissolved oxygen level, which has an impact on nutrient and metal interactions. Vascular plants play several key roles in the treatment of wastewater and runoff, including stabilising substrates and limiting channelized flow, slowing water velocities to allow suspended materials to settle, absorbing carbon, nutrients, and trace elements and incorporating them into plant tissues, transporting gases between the atmosphere and the sediments, providing oxygen to the area around the roots, and providing sites for microbial attachment to grow on [16] and create litter when they die and decompose [34].

The effectiveness of a manmade wetland can be increased by diversifying the plant communities, but it is challenging to maintain polyculture without a physical barrier to prevent the plants from outgrowing one another [35].

Various plants used in CWs include *Eichhornia crassipes* (Water Hyacinths), *Kochia spp.* (Forage Kochia), *populus spp.* (Poplar Trees), *Salix spp.* (Willow Trees), *Medicago sativa* (Alfalfa), *Typha latifolia* (Cattail), *Ceratophyllum demersum L* (Coontail), *Scirpus spp.* (Bulrush), *Phragmites spp.* (Reed), *Cyperus articulatus* (Jointed flatsedge), *Potamogeton nodosus* (American pondweed) and *Sagittaria latifolia* (common Arrowhead). Table 6 below highlights potential plants for constructed wetlands commonly used in the East African region.

Table 6: Potential Plants for subsurface flow CWs often used in East African region

Plant names	Common names	Uptake capacity(kg/ha.Year)	
		Nitrogen	Phosphorus
Cyperus papyrus	Papyrus	1100	50
Cyperus papyrus	Reed	2500	120
Typha sp.	Cattail	1000	180
Scirpus sp	Bulrush	-	-
Cyperus articulate	Jointed flatsedge	-	-
Vetiveria zizanoides	Vetiver	-	-

2.4.6 Constructed wetland microorganisms and animals

The fact that microorganisms and their metabolism heavily control the functioning of wetlands is one of their defining characteristics. Microorganisms include bacteria, yeasts, fungi, protozoa, and rind algae. Among them, *pseudomonas aeruginosa*, *Escherichia coli*, *Bacillus subtilis*, *Clostridium chauvoei*, *Clostridium septicum*, and *Staphylococcus sp.* are explicitly mentioned [18]. A significant sink for organic carbon and a variety of nutrients is the microbial biomass. Numerous organic and inorganic chemicals are converted by microbial activity into harmless or insoluble forms, the redox conditions of the substrate are changed, which has an impact on the wetland's ability to utilise nutrients, and nutrients are recycled. While certain microbial processes are anaerobic, others are aerobic. Numerous bacterial species are facultative anaerobes, which means they can operate in both aerobic and anaerobic environments [40].

Microbial communities adapt as the water that is provided to them changes. Microbe populations can grow swiftly when given access to the right materials that contain energy. Many microorganisms go dormant when the environment is no longer favourable, and they can stay inactive for years. Toxic compounds, such as pesticides and heavy metals, can have an impact on the microbial population of a constructed wetland, thus caution must be taken to avoid introducing them at harmful amounts [40].

Constructed wetlands are home to a wide variety of invertebrates and vertebrates for animals. By tearing up debris and devouring organic waste, invertebrate animals like worms and insects aid in the treatment process. Many insect larvae are aquatic and gobble up a lot of material when in their larval stages, which can persist for years. Additionally, invertebrates have a variety of ecological roles. For example, mosquito larvae are effectively preyed upon by dragonfly nymphs. Although invertebrates are the most crucial species for improving water quality, a variety of amphibians, turtles, birds, and mammals are additionally attracted to artificial wetlands [40].

2.4.7 Performance efficiency of HSSFCWs as a case in other countries

The results follow was obtained during the research conducted to measure the effectiveness of HSSF constructed wetlands treating wastewater.

In Kenya; BOD₅:98%, COD: 96%, TSS: 85%, TN: 90%, NH₄⁺-N: 92% and PO₄³⁻ : 88% during treatment of domestic wastewater. In Indonesia; COD: 98.46% and BOD₅: 98.55%. In Costa Rica; BOD₅: 94-99.9%, COD: 91.7-97.9% and TFC: 99.99%. While in Ethiopia, the HSSFCW achieved these results: BOD₅ : 99.3%, COD :89%, TSS: 85.5%, TN : 84.05%, PO₄³⁻ : 77.3%, TP: 99% and TFC : 94.5% for domestic wastewater treatment [10].

2.4.8 Contaminant removal processes in constructed wetlands

In a constructed wetland, the processes that help remove pollutants are typically divided into two categories: constituent transformations and liquid/solid separations [41]. Gravity separation, filtration, absorption, adsorption, ion exchange, stripping, and leaching are a few common separation techniques. Chemical transformations include oxidation/reduction, flocculation, acid/base, breakdown, precipitation, and biochemical reactions (biochemical absorption) that take place under aerobic or anaerobic circumstances and are aided by the root zone environment [42].

Removal of contaminants from wetlands may result via separations and transformations. Physical, chemical, and biological processes are the three types of processes used in CWs to remove pollutants [9], [17]. By adding oxygen, wastewater is treated so that microorganisms may use the nutrients in the wastewater as food. Constructed wetland efficiency may fluctuate seasonally since the microbiological processes engaged in these processes are often temperature-dependent, although the overall average performance is satisfactory [43].

The root zone interactions between soil, pollutants, helophyte roots, and a range of microorganisms determine how effectively CWs remove pollutants from wastewater. The primary medium for plant and microbial growth is the soil. According to reports, fine gravel encourages more plant growth, which accelerates the elimination of pollutants. By releasing oxygen in the root zone, helophytes that immediately contribute to the intake of nutrients and the direct breakdown of contaminants. As a result, contaminants are aerobically degraded and given microbial activity. The concentration of the compounds, as well as their physicochemical properties (such as their acidity constant (pKa), log KOW, and octanol water partition coefficient (log KOW), among others), are the main variables that affect the uptake of organic pollutants by plants [43] which divides the metabolism of contaminants in plants into three stages which are transformation, conjugation and compartmentation.

The primary regulators of the functions of CWs are microorganisms and their metabolism. Algae, yeast, fungi, bacteria, and protozoa are examples of microorganisms that are crucial to the biogeochemical transformation of nutrients. They can also change the reduction/oxidation conditions of the substrate and remove hazardous organic molecules through aerobic or anaerobic degradation processes [35]. The two main processes by which microbes convert organic contaminants into harmless substances like CO₂, N₂, and H₂O are respiration and fermentation [44].

2.4.8.1 Suspended solids removal

The most common methods of removing suspended particles are filtration, flocculation, and sedimentation [35], [16]. Different sorts of pollutants, including nutrients, heavy metals, and organic substances, may be present in wastewater's suspended particles. Vander Waal's force of attraction and electric forces, which can be either attracting or repulsive depending on the surface charges, are two additional surface forces that contribute to the decrease in suspended solids [14].

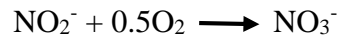
2.4.8.2 Nitrogen removal

Eutrophication in waterbodies that receive domestic wastewater can be brought on by high nitrogen concentrations. On the other hand, there are several kinds of organic and inorganic nitrogen, both of which are necessary for all living things. Numerous processes in CWs, including adsorption, volatilization, plant adsorption and uptake, ammonification and nitrification (in the aerobic zone), and denitrification (in the anaerobic zone), can remove nitrogen from wastewaters [11]. These are the most significant eradication procedures from the CWs' root zone [11].

Ammonium (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-), which are the inorganic forms of nitrogen contained in wastewater, are eliminated by plant absorption at low hydraulic loading rates. Helophytes transform inorganic nitrogen forms found in constructed wetlands into organic chemicals that serve as parts of cells and tissues. Depending on the types of nitrogen present in the substrate, many macrophytes species have different preferred ways of nitrogen absorption [42].

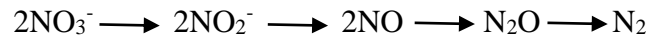
Nitrification and denitrification, which are aided by microorganisms, are the main nitrogen removal processes during wastewater treatment in wetlands. The process of nitrification is the aerobic oxidation of ammonium to nitrate with the help of nitrifying microorganisms. It consists of these two steps: *Nitrosomonas* bacteria converting ammonium to nitrite, and *Nitrobacter* bacteria converting nitrite to nitrate. The nitrifying bacteria use carbon dioxide as a carbon source and generate energy from the oxidation of ammonia and nitrite during this process [45].

The overall reactions for these two steps are:



Temperature, pH level, water alkalinity, inorganic carbon supply, moisture, microbial population, Ammonium-N and dissolved oxygen concentrations, among other factors, all affect nitrification.

Organic matter is broken down by microbes including *Pseudomonas*, *Micrococcus*, and *Bacillus* during the anaerobic decomposition process known as denitrification, which uses nitrate as an electron acceptor instead of oxygen. Nitrate is reduced to nitrous oxide, which is then further reduced to nitrogen gas during the two-step denitrification process [45]. The following equation illustrates denitrification.



In CWs, denitrification is responsible for 60 to 70% of the TN elimination. Numerous variables, including nitrate concentration, microbial flora, type and quality of organic carbon source, hydroperiods, residues from various plant species, lack of oxygen, redox potential, soil moisture, temperature, pH value, presence of denitrifiers, soil type, water level, and presence of overlying water, can affect the rate of denitrification [45].

In the intricate biochemical process known as ammonification, organic N is physiologically transformed into ammonia through a number of intermediary processes. In the aerobic regions of the substrate, ammonification takes place more quickly than nitrification. The pH, temperature, carbon to nitrogen (C/N) ratio, amount of accessible nutrients, and substrate properties can all affect how quickly it grows. Ionised ammonia is adsorbed in CWs by a cation exchange process with the substrate. Only SSF CWs, where there is effective contact between the substrate and the effluent, can undergo this nitrogen removal process. Additionally, the removal of nitrogen in the form of ammonia through volatilization may be important [45].

2.4.8.3 Phosphorous removal

The conditions for the interconversion of all forms of phosphorus are provided by CW. Different wastewaters include phosphorus in both organic and inorganic forms. Until they are converted into soluble inorganic forms, dissolved organic phosphorus and insoluble forms of organic and inorganic phosphorus are typically not physiologically accessible [14].

Helophytes absorb soluble reactive phosphorus, which they then convert to tissue phosphorus or may sorb to CW substrate. Helophytes typically absorb the most phosphorus at the start of the growing season, before their maximum growth rate is attained [14].

Sediment retention is the main method used to extract phosphorus from wastewater. Peat/soil accretion, adsorption/desorption, precipitation/dissolution, plant/microbial absorption, fragmentation, leaching, and mineralization are phosphorus transformations that occur in wetlands [45], [11]. Long-term phosphorus sequestration in wetlands is controlled by soil adsorption. Adsorption is the term used to describe the transport of soluble inorganic P from soil pore water to mineral surfaces of the soil, where it accumulates without penetrating the soil surface. Apatite, Hydroxylapatite, Variscite, Strengite, Vivianite, and Wavellite are amorphous or weakly crystalline minerals that form during precipitation, which is a reaction between phosphate ions and metallic cations such as Fe, Al, Ca, or Mg. This process takes place in the wetland environment [14].

2.4.8.4 BOD and COD removal

BOD and COD elimination were discovered to happen quickly by particle matter settling and trapping in the void areas in the gravel or rock media. Aerobic microbial decomposition and sedimentation/filtration processes are the principal causes of BOD removal in CWs [11]. Microbial development on media surfaces and affixed to plant roots and rhizomes remove soluble organic substances. A variety of microbes use the carbon (C) that makes up organic matter, which ranges from 45 to 50%, as a source of energy [11]. Helophytes in the root zone provide oxygen for this process, which turns organic carbon into carbon dioxide. Additionally, soluble organic waste may be eliminated using a variety of separation techniques, including adsorption and absorption. The features of the organic matter and the solid surface (helophytes, substrate, and litter) determine the level of sorption and its rate [35].

In wetlands, biochemical transformations are crucial pathways for degradable organic matter. They might explain how some organic components are eliminated through mineralization or gasification, and how organic matter is created through the synthesis of new biomass. By way of mineralization and gasification, the decomposers found in CWs, such as fungi and bacteria, play a significant part in the removal of organic matter [47].

Biomass synthesis and the creation of organic metabolic end products are both carried out by decomposers. Phytovolatilisation is a significant phenomenon for the elimination of pollutants in addition to these other factors. Additionally, some wetland plants absorb pollutants through their roots and release them into the atmosphere through their transpiration stream [46]. Volatilization/Phytovolatilisation is a method that directly removes hydrophilic substances like acetone and phenol.[47] .

2.4.8.5 Pathogens removal

CWs are very good at removing pathogens [43]. Through a mix of physical, chemical, and biological processes, a wetland functions as a biofilter by reducing the number of pathogens. Aggregation, filtration, sedimentation, and solar ultraviolet radiation exposure are examples of physical mechanisms. Adsorption, oxidative damage, and exposure to poisons released by other microbes and plants are a few examples of chemical pathways. The biological causes include natural mortality, nematode, protozoan, lytic bacterial, and bacteriophage attacks. Choudhary et al. [14] observed that created wetlands reduced faecal coliform populations up to 99% and eliminated coliforms > 90% and streptococci > 80% in diverse systems of constructed wetlands.

The table 7 below summarizes pollutants removal mechanisms in constructed wetlands.

Table 7: Summary of pollutants removal mechanisms in constructed wetlands [19], [42].

Parameters	Physical	Chemical	Biological
Suspended solids	Sedimentation and Filtration		Biodegradation
Chemical oxygen Demand	Sedimentation and filtration, accumulation	Reduction and oxidation	Biodegradation
Biological oxygen Demand	Sedimentation and filtration	Reduction and oxidation	Biodegradation, Plant uptake, Phytovolatilisation, Fermentation, Phytodegradation,
Nitrogenous compound	Sedimentation and volatilization	Adsorption	Bio denitrification, nitrification, plant and microbial uptake
Phosphoric compound	sedimentation	Adsorption and precipitation	Microbial uptake and plant uptake
Pathogens	Filtration and UV ray action	Adsorption and oxidation	Natural death, exposure to natural toxins (antibiotics of macrophytes roots) and bacteriophage attack (predation).

2.4.9 Factors affecting the performance of constructed wetlands

The operational conditions of HSSFCWs, such as temperature, pH, plant species, hydraulic retention time, hydraulic loading rate, dissolved oxygen, microbial communities, soil/substrate/media type, feeding mode, contaminants, presence of organic carbon, recirculation, plant harvesting, and wetland depth, have an impact on the performance efficiency sustainability of constructed wetland systems [10], [24].

2.4.10 Constructed wetland operation and maintenance

Simple but consistent maintenance is needed for constructed wetlands; the hydraulic and organic load should be evaluated frequently and should not exceed the design values, and careful management of organic loadings can also aid in mosquito population control [32]. While created wetlands with a single unit can accomplish the appropriate degree of treatment, using many cells makes maintenance easier. Whether or not CW Plants should be harvested is still up for debate, plants need to be harvested if they interfere with operational and maintenance tasks [36]. In Tanzania, constructed wetlands often had issues with clogging, flooding, leakage, overloading, and storm water runoff. All of these issues could have been avoided with proper planning, which included taking into account safety factors and continuous surveillance [36].

2.4.11 Treated domestic wastewater effluent management

Wastewater can be safely recycled or released into receiving water bodies by using constructed wetlands that are designed to satisfy regulatory requirements. Reuse in agriculture, recreation, the environment, industry, and groundwater recharge are all possibilities for treated effluent. Reusing residential wastewater offers a tremendous chance to lessen the need for municipal drinking water for activities like gardening and other uses that call for lower water quality. While a manmade wetland at Ruaha Secondary School in Tanzania is used for students to learn, the effluent from the wetland is used to cultivate elephant grass for the cows there [48].

CHAPTER 3: MATERIALS AND METHODS

3.1 Description of the study area

The Excella School is an international school founded in 2008 and located in Kimironko Sector, Gasabo District and at the south edge of Nyabugogo catchment in Kigali, Rwanda (figure 6). The school offer education at the primary school level, the secondary school level and the high school level with boarding school facilities at secondary school level. To treat its black water, the school has built a horizontal sub-surface flow constructed wetlands with a capacity of around 1270 population and this system receive the wastewater influent from septic tanks. The constructed wetland system at Excella School is a full-scale system composed of two equal parallel basins sized at about 208 m² and 0.8 m of depth for each basin which is planted with *Cyperus articulatus* (Ubusuna) and treated effluent is released in the nearby natural wetland. The figure 7 shows the layouts of the studied HSSFCWs with the fixed sampling points in which: 2 sampling points at the outlet of HSSFCWs (1 sampling point at effluent 1 (E₁), and 1 sampling point at effluent 2 (E₂)) and 1 influent sampling point at outlet of septic tank.

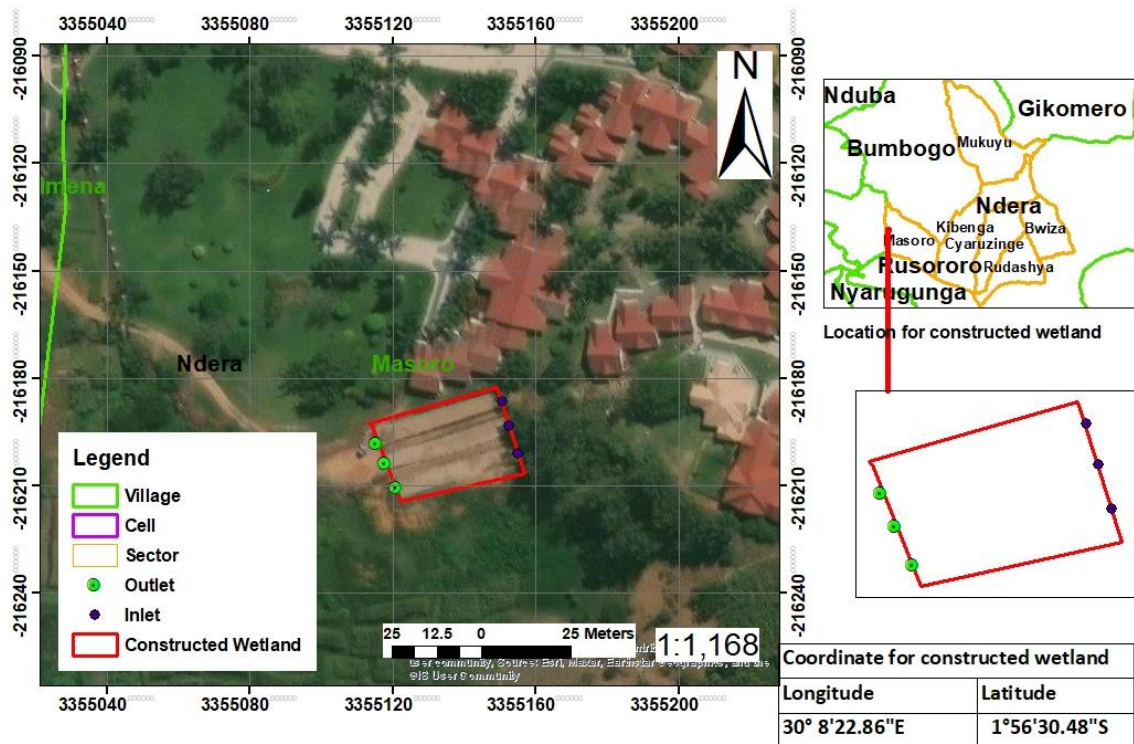


Figure 6: Map showing the location of Excella School at the edge of Nyabugogo Catchment

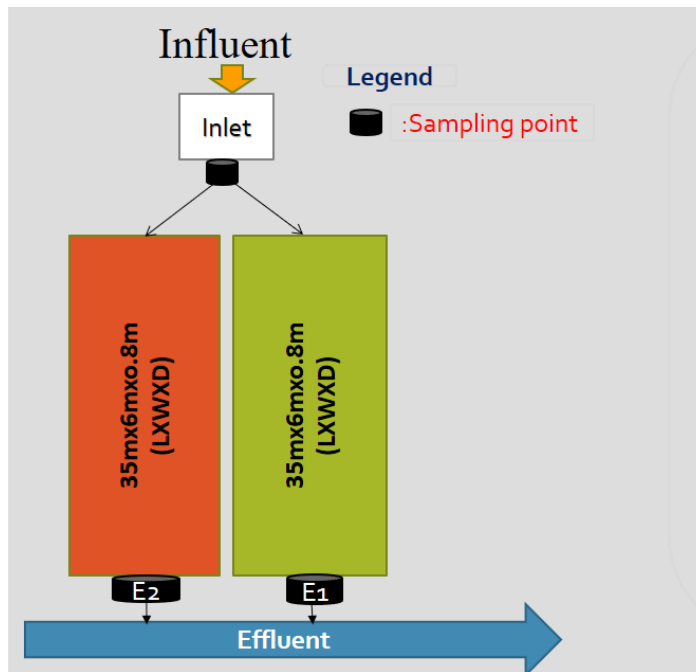


Figure 7: Schematic diagram of the CWs showing the layout and sampling points

3.2 Sampling methods

To evaluate the removal efficiency of organic matter, nutrients and pathogens of local full scale horizontal sub-surface flow constructed wetlands and to study the appropriate reuse of the effluent for irrigation in Kigali, duplicates grab wastewater samples were collected manually in 500 mL plastic clean bottles, every 2 weeks within a period of 6 months from October 2022 up to March 2023. Wastewater samples were collected from 3 sampling points at the HSSFCWs located at Excella School in Kigali as shown by the diagram in figure 7.

Polyethylene plastic bottles and sterilized Duran glass bottles for microbiological and BOD₅ samples were used in sample collection and they were preserved in cooler boxes at 4°C, then after they were transported and preserved carefully in CST Chemistry laboratory. Wastewater Samples for total nitrogen (TN) were analysed directly. Water samples were kept at 4°C in refrigerator until analysis.

3.3 Methods of analysis and materials

To assess the removal efficiency of the HSSFCWs through the 2 basins: field visits, water sampling and analysis were performed. Parameters that were analysed include: pH, Temperature, Electric conductivity, TDS, BOD₅, COD, TN, TSS, TP, Total coliform, fecal coliform and Escherichia Coli. The existing laboratory at UR-CST was used for the water quality analysis. The analysis was conducted according to the 23rd edition of Standard Methods for The Examination of Water and Wastewater.

Parameters such as temperature, pH, TDS, and electrical conductivity were measured in situ using HACH field testing kits. TP and TN were determined by using Persulfate Digestion method and quantified by using UV-Vis spectrophotometer at $\lambda = 690\text{nm}$ and $\lambda = 543\text{ nm}$ respectively. Chemical Oxygen Demand was determined by closed Reflux, colorimetric method (5220D) while Biological Oxygen Demand was determined by using BOD electrode method (BOD₅, 5210B), TSS was determined by Gravimetric method (2540D). TC, FC and *E-coli* were determined by multiple-tube fermentation technique for members of the coliform group (9221B, E, F) [49].

3.4 Pollutant removal efficiency estimation

Pollutants removal efficiencies (RE) from HSSFCWs at Excella School were calculated as shown in the equation below by assuming that the wastewater discharge at the inlet and outlet is almost the same:

$$RE = \frac{\text{Influent Concentration} - \text{Effluent Concentration}}{\text{Influent Concentration}} \times 100 \quad (2)$$

3.5 Method of biodegradability index determination

The ratio of BOD₅ to COD is known as the biodegradability index (BI), which serves as an indication of the wastewater's toxicity. The range of its value is 0 to 1. To conserve aquatic life in the receiving water bodies, it is preferred that an effluent have a BI as low as possible. The ability of a material to spontaneously break down into smaller components, such as sugars and gases, by the organisms such as bacteria and fungi in an environment is known as biodegradability [50]. Utilizing the equation 3 BI is determined.

$$BI = \frac{BOD_5}{COD} \quad (3)$$

3.6 Method of comparing the effluent from HSSFCWs treating domestic wastewater at Excella School in Kigali with the standards of water reuse for irrigation.

Currently the treated effluent is released to the adjacent natural wetland used for agriculture activities. To determine if this water can be reused for irrigation, the methodology proposed by the standards below were used:

1. RS ISO 20419:2018 “Treated wastewater reuse for irrigation - Guidelines for the adaptation of irrigation systems and practices to treated wastewater” was used. In fact, the guideline provides specifications on the quality of the treated wastewater (TWW) that can be used for irrigation. The table 8 below provides specifications on the quality of the TWW that can be used for irrigation [51].

Table 8: TWW quality for irrigation

Parameter	Good TWW quality^a	Good TWW quality^b	Good TWW quality^c
BOD (mg/l)	< 10	10 to 50	>50
COD (mg/l)	< 50	50 to 80	> 80
TSS (mg/l)	< 30	30 to 70	> 70
pH	6 to 7.5	7.6 to 8	>8

2. RS188:2019 “Water quality-water irrigation-tolerable limits”. This standard provides requirements for irrigation water quality. RS 188 was prepared by technical committee RSB/TC13, water and sanitation. The table 9 below provides the irrigation water characteristics.

Table 9: Irrigation water characteristics

Characteristics	Degree of restriction of use		
	Non problems	Increasing problems	Severe problems
pH	< 6.5	6.5-8.4	> 8.4
TDS (mg/l)	< 450	450-2000	> 2000
EC (mmhos/cm)	< 0.75	0.75-3	> 3

It is important to study the microbiological and biochemical characteristics of effluents before using them for irrigation. The effluent should only be evaluated in terms of chemical criteria like dissolved salts relative sodium content and specific toxic ions when it complies with public health standards, which should be compared to these values after taking the crop, soil, irrigation system, and consumption of the produce into account [52].

CHAPTER 4: RESULTS AND DISCUSSION

In this chapter, the results of different parameters obtained during laboratory analysis were presented and discussed by comparing with Standards and the findings of others researches conducted on constructed wetlands. Average Nutrients, organic matter, pathogens removal efficiencies in HSSFCWs and average biodegradability index (BI) of the effluent were presented and discussed in this section. Comparing the effluent with the standards of water for irrigation was also done in this chapter and detailed results of nutrients, organic matter, pathogens, BI and other tested parameters were presented in appendices.

4.1 Organic matter Removal

4.1.1 Biochemical Oxygen Demand removal (BOD₅)

BOD₅ measures the oxygen required by bacteria to decompose biodegradable organic matter present in wastewater during five days. In this study, removal of Biochemical Oxygen Demand from HSSFCWs increased as time went on during the period of monitoring as shown in appendix 1, table 2 figure 1. The influent BOD₅ concentrations during the period of the study were ranged from 175 mg/L to 231 mg/L with the average concentration of 211.4 ± 16.9 mg/L while the effluent BOD₅ concentrations were ranged from 65 mg/L to 120 mg/L, with the average concentration of 95.7 ± 21.7 mg/L.

During the study period, the removal efficiency of BOD₅ was ranged from 45.5 % to 69 %. The average removal efficiency of BOD₅ in the whole study period was 54.9 ± 8.5 % and study conducted in Egypt, the Phragmites planted unit showed higher performance with removal efficiency of 68 % of BOD₅ [13] and 68.5 % which is reported by Mburu in Kenya [20].

Generally, the increase of the removal efficiency of BOD₅ during the study period is due to the wetlands microorganisms and plants growth which increase the oxygen in the root zone of the plants and that oxygen was used for BOD break down by microorganisms [18]. Organic contaminants in settleable forms are treated by deposition, filtration, microbial degradation (aerobic & anaerobic), and plant uptake. Microbial degradation is the predominant process in removing the BOD₅ [11]. The figure 8 below shows the Comparison of BOD₅ concentration with RSB standard.

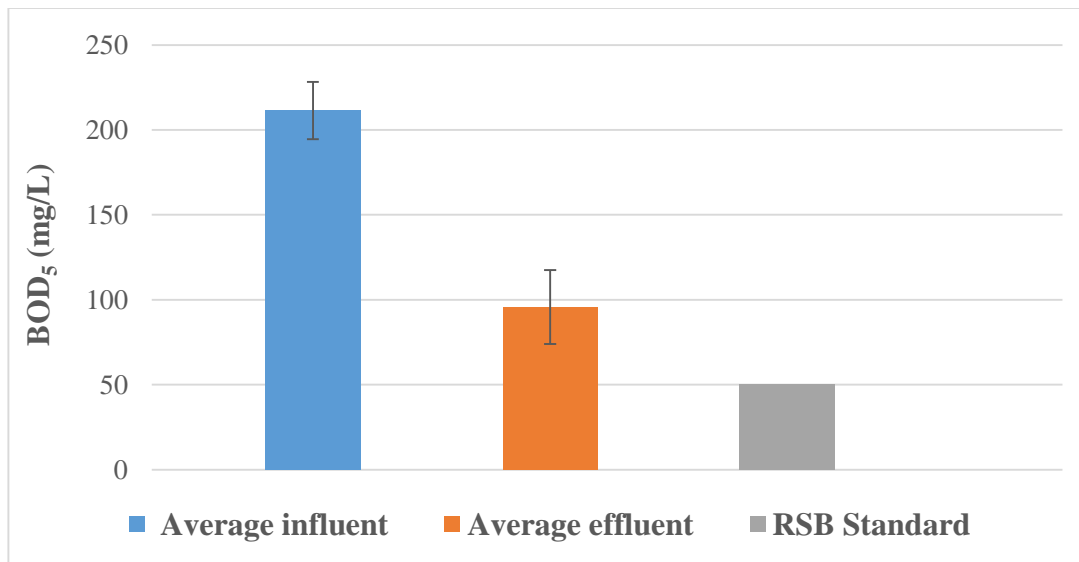


Figure 8: Comparison of BOD₅ concentration with RSB standard.

As show in figure 8, BOD₅ influent and effluent concentrations exceed 50 mg/L of RSB standard of wastewater to be released in the environment during the whole period of the study.

4.1.2 Chemical Oxygen Demand (COD)

The COD is explained as the amount of a specified oxidant that reacts with a sample under controlled conditions. The quantity of oxidant consumed under controlled conditions is expressed in terms of its oxygen equivalence. During this research, removal of Chemical Oxygen Demand from HSSFCWs increased as time went on during the period of monitoring as shown in appendix 1, Table 4 and figure 2. The influent COD concentrations during the period of the study were ranged from 250 mg/L to 315 mg/L with the average concentration of 284.6 ± 21 mg/L while the effluent COD concentrations were ranged from 85 mg/L to 136.6 mg/L, with the average concentration of 122.8 ± 22.7 mg/L.

The removal efficiency of COD was ranged from 46 % to 69.8 %. The average removal efficiency of COD in the monitoring period was 56.8 ± 7.1 %. In a similar type of study in Tanzania, a *phragmites mauritianus* planted unit showed removal efficiency of 56.3 % for COD which is around what we have seen in our study [13]. In another hand, the study conducted in Kenya showed a removal efficiency of 96% which is greater than what we found in this research [10].

Furthermore, the increase of the removal efficiency of COD during the monitoring period is due wetlands microorganisms and plants growth which increased the oxygen in the root zone of the plants which was used for COD break down by microorganisms[18]. Organic contaminants in settleable forms are treated by sedimentation, filtration, accumulation, biodegradation, reduction, oxidation and plant uptake [42]. The figure 9 below shows the Comparison of COD concentration with RSB standard.

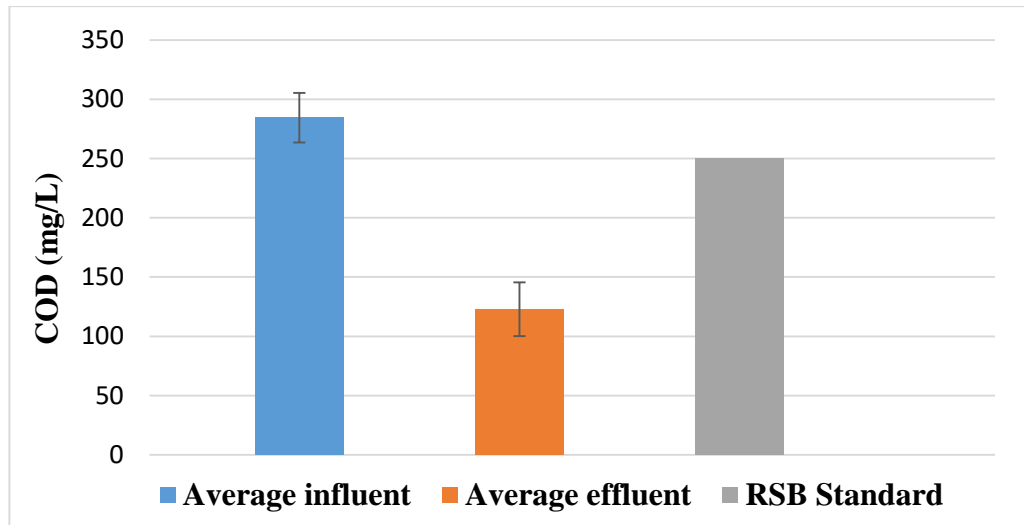


Figure 9: Comparison of COD concentration with RSB Standard.

As illustrated in figure 9, COD effluent concentrations were under 250 mg/L of RSB standard during the whole period of the study and effluent COD concentrations met the requirements of the domestic wastewater to be released in the environment [28].

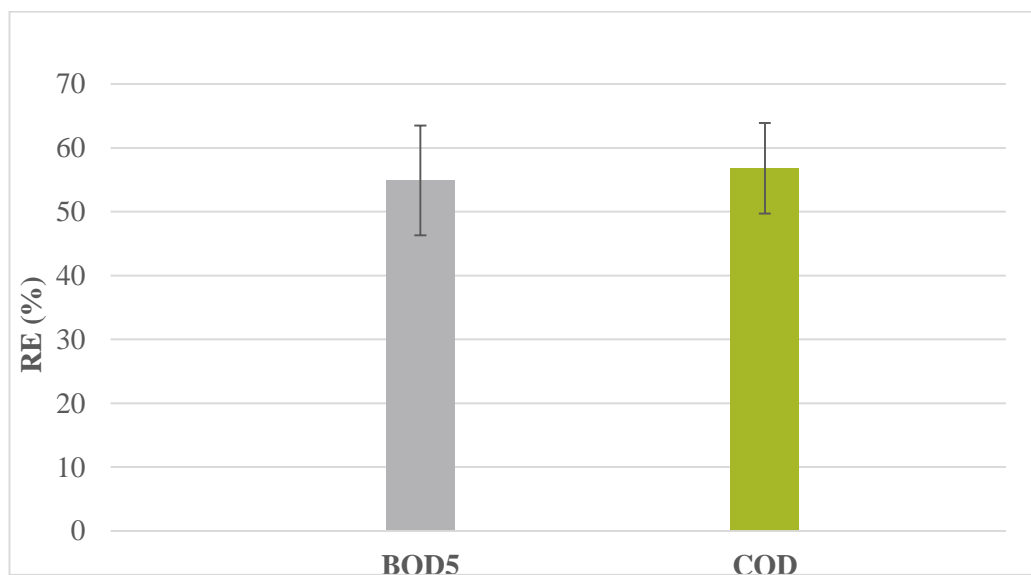


Figure 10: RE of COD and BOD₅ in HSSFCW at Excella school in Kigali

4.2 Biodegradability index (BI) of the effluent at Excella School in Kigali

BOD₅/COD ratio of wastewater is referred to as the biodegradability index (BI), usually used to estimate the likelihood of organic components degradation in wastewater prior to treatment [50]. Wastewater with BOD₅/COD value greater than 0.6 or ranging from 0.4 to 0.8 is considered as biodegradable and could be effectively treated biologically. The second specific objective was to determine biodegradability index of the effluent from local horizontal subsurface flow constructed wetlands treating domestic wastewater at Excella School in Kigali and it was deduced from COD and BOD₅ as indicated in equation (3).

As shown in appendix 2, Table 2, BI obtained during the monitoring period of the study were in the biodegradability range of organic matter in natural wastewater treatment system. For influent, BI were ranged from 0.7 to 0.81 with the average of 0.74 ± 0.04 while for the effluent, BI were ranged from 0.63 to 0.88 with the average value of 0.78 ± 0.1 .

As discussed above, municipal wastewater is considerably to be biodegradable when BI is above 0.6. Therefore, this indicated that biological treatment is the more preferred method of treatment for influent and effluent over the chemical means. The high biodegradability index is due to the high amount of biodegradable matter compared to the amount of non-biodegradable matter. For the sustainability of aquatic organisms, it is essential for the surface water to have reduced level of BOD₅/COD values. Therefore, the effluent wastewater is not favorable to be discharged into the environment and there is no sustainability of aquatic organisms. The DO concentration in water is inversely proportional to BOD₅/COD level [53].

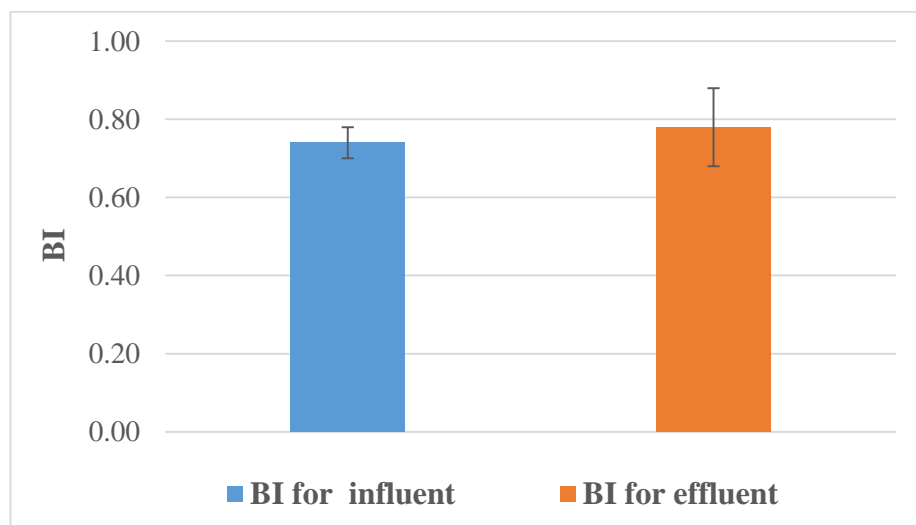


Figure 11: BI of influent and effluent for HSSFCWs at Excella School

4.3 Nutrients Removal

4.3.1 Total nitrogen (TN) removal

As show in appendix 3, table 2 and figure 1, TN removal from HSSFCWs increased as time went on during the period of monitoring. The influent TN concentrations during the period of the study were ranged from 1.8 mg/L to 4.4 mg/L with the average concentration of 2.4 ± 0.8 mg/L while the effluent TN concentrations were ranged from 0.7 mg/L to 2.1 mg/L, with the average concentration of 1.3 ± 0.4 mg/L.

Ammonification and nitrification processes are the basics mechanisms for nitrogen removal in CWs. Ammonification transforms the influent organic nitrogen into ammonia and nitrification oxidizes ammonium into nitrogen oxidized forms (NO_x-N). Both processes are favored at the range of temperature of 25 to 35°C and in addition for nitrification, pH around 7.5 are also the factors which favor nitrification[54].

From appendix 5 of other tested parameters, table 6 and table 2 showed that the average temperature and pH were around 22.4 and 8 respectively and these results showed that none of them which favor nitrification, these could explain the reason why the TN removal efficiency is generally low. In addition to these, the plant in the HSSFCWs at Excella school are still growing and one part in the HSSFCWs, the plants were not growing and they are the major contributor in nutrients removal through plant uptake. Furthermore, Nitrogenous compounds are removed from constructed wetland by sedimentation, volatilization, adsorption and microbial uptake[33].

The removal efficiency of TN during the study period was ranged from 30 % to 65 % with the average RE of 46 ± 12.5 %. Study conducted in Indonesia, *Typha latifolia* planted unit showed high removal efficiency of 76.37 % of TN which is greater than what we have seen in our study [18]. Another similar study conducted in Ethiopia showed the high average removal efficiency of 54% of TN which is also greater than what we have seen in our study [55]. The figure 12 below shows the Comparison of TN concentration with RSB standard.

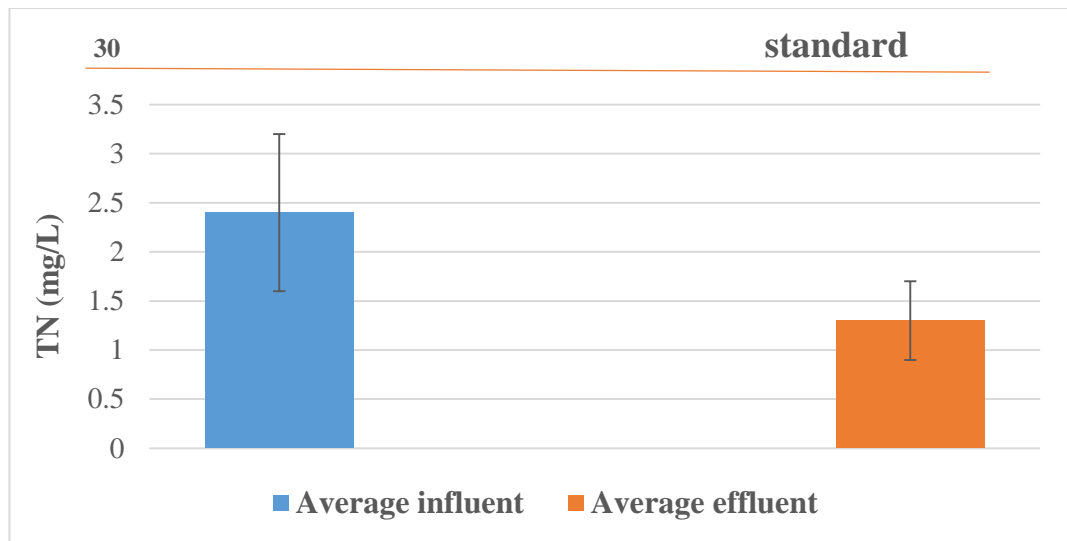


Figure 12: Comparison of TN concentration with RSB standard.

As indicated in figure 12 which is above, Total nitrogen effluent concentrations were under 30 mg/L of RSB standard during the whole period of the study and effluent TN concentrations met the requirements of the domestic wastewater to be released in the environment [28].

4.3.2 Total phosphorus (TP) removal

As illustrated in appendix 3, table 4 and figure 2, TP removal from HSSFCWs increased as time went on. The influent TP concentrations during the period of the study were ranged from 3.6 mg/L to 7.6 mg/L with the average concentration of 5.8 ± 1.2 mg/L while the effluent TP concentrations were ranged from 1.4 mg/L to 3.9 mg/L, with the average concentration of 3 ± 0.8 mg/L.

The main methods used to remove phosphorus from constructed wetland are medium adsorption and plant uptake [56]. In the majority of wetland investigations, the soil compartment has been identified as the main long-term Phosphorous storage pool. The elimination of phosphorus in artificial wetlands is not affected by temperature. The most significant mechanisms for removing phosphorus are chemical precipitation and physico-chemical sorption which are not temperature-dependent, hence temperature has little impact on this process [57]. Phosphorus can also be removed by sedimentation and microbial uptake in addition to the previously stated removal processes [11].

During the study period, the removal efficiency of TP was ranged from 27.3 % to 61.1 % with the average RE of 47.9 ± 10.2 %. By comparing RE of our study with the similar study, The removal efficiency obtained was higher than the removal efficiency reported in Kenya which was 26% [58] but less than the removal efficiency of 85.26% of TP which was reported in Indonesia[18]. The figure 13 below shows the Comparison of TN concentration with RSB standard.

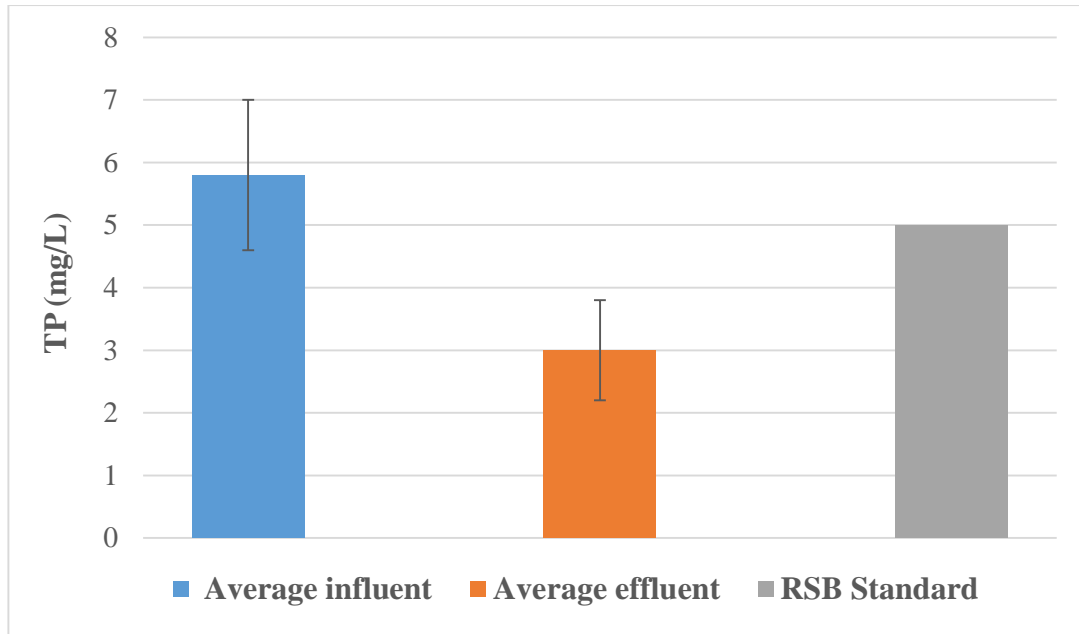


Figure 13: Comparison of TP concentration with RSB standard

As shown in figure 13 which is above, Total phosphorus effluent concentrations were under 5 mg/L of RSB standard during the whole period of the study and effluent total phosphorus concentrations met the requirements of the domestic wastewater to be released in the environment [28]. Figure 14 below shows RE of TN and TP in HSSFCW at Excella school in Kigali.

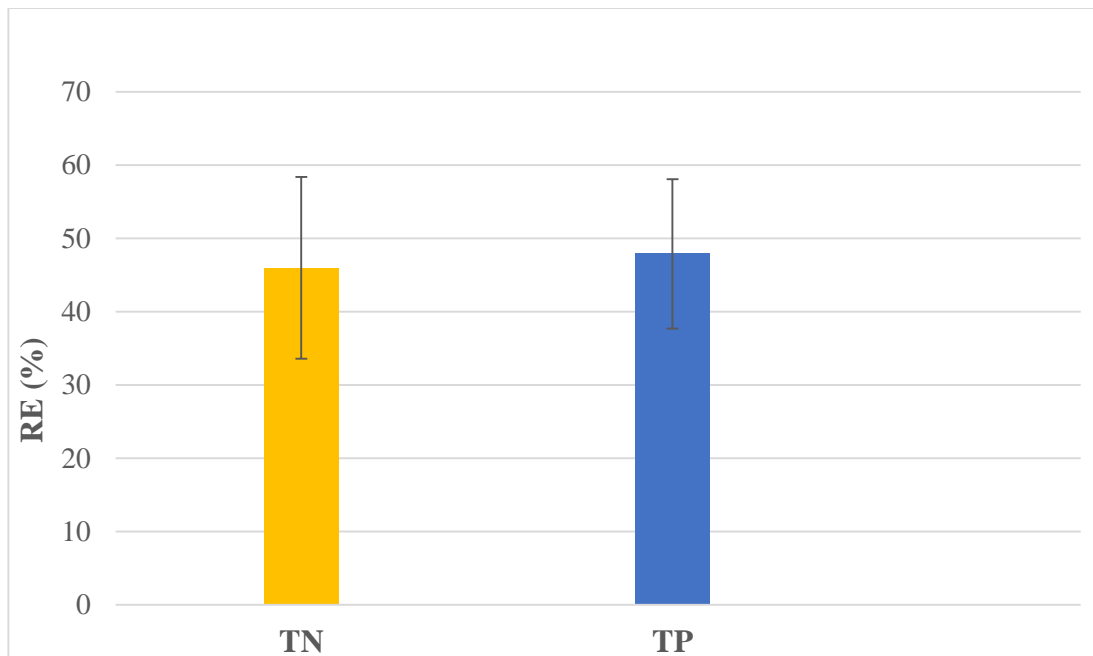


Figure 15: RE of TN and TP in HSSFCW at Excella school in Kigali

4.4 Pathogens removal

Typically, pathogens are microorganisms that cause or have the potential to cause disease. Pathogens in CWs can be eliminated through the use of UV rays, adsorption, sedimentation, filtration, oxidation, natural death, antibiotic exposure of macrophytes roots, and predation [14]. The primary pathogen elimination process in wastewater treatment systems is sedimentation. The fact that pathogens can build up in large quantities in CW sediments and medium grains suggests that bottom gravel layers might serve as a pathogen sink. Adsorption of microorganisms also happens to filter media grain or sediments, plant roots, and the resulting biofilm. The size and kind of particles attached have an impact on the adsorption of coliform bacteria. Plants are supposed to increase the effectiveness of CW in removing pathogens because bacteria are more likely to develop and be active when there is a biofilm and due to the fact that more oxygen is available [43].

4.4.1 Total coliforms (TC) removal

Total coliforms (TC) are encompassing faecal coliforms as well as common soil microorganisms, and are a broad indicator of possible water contamination. The table 15 shows the sampling date, concentrations of TC and the removal efficiency for constructed wetland at Excella School. The average influent concentration was 172.168×10^3 CFU/100 ml while the average effluent concentration was 2.598×10^3 CFU/100 ml which was high compared to 400 CFU/100 ml of RSB standard. Therefore, TC effluent concentration didn't meet the requirements of the domestic wastewater to be released in the environment. In addition, the average removal efficiency for our study was 94.58 % and a study conducted in Indonesia, planted unit macrophytes *T.latifolia* and *Commelina benghalensis* showed removal efficiency of TC of 64 % which is less than to what was obtained in this study[11].

4.4.2 Faecal coliforms (FC) removal

A sign of faecal matter contamination in water is faecal coliforms (FC). *Escherichia coli* (*E. coli*) bacteria are a typical lead indicator. Faecal coliforms is a rod-shaped, gram-negative, facultative anaerobic, non-sporulating bacteria. Warm-blooded animals' intestines are where coliforms bacteria are typically found to first appear [43].

The table 16 indicates the sampling date, concentrations of FC and the removal efficiency for constructed wetland at Excella School. The average influent concentration of FC was 203.94×10^2 CFU/100 ml while the average effluent concentration of FC was 8.91×10^2 CFU/100 ml which was high compared to 400 CFU/100 ml of RSB standard. Therefore, FC effluent concentrations didn't meet the requirements of the domestic wastewater to be released in the environment. In addition, the average removal efficiency for our study was 95.60 %. The similar studies conducted in US by Neralla et al. showed the reduction in populations of faecal coliforms by 90–99% [59].

4.4.3 *Escherichia Coli (E-coli)* removal

E-Coli is a type faecal coliforms bacteria that is commonly found in the intestines of animals and humans. E-coli in water is a strong indicator of sewage or animal waste contamination. The table 17 indicates the sampling date, concentrations of *E-Coli* and the removal efficiency for constructed wetland at Excella School. The average influent concentration of *E- coli* was 47.49×10^2 CFU/100 ml while the average effluent concentration was 0.47×10^2 CFU/100 ml. The average RE of *E-Coli* for our study was 98.89 %. The constructed wetland performed well during the maturity period of macrophytes [60]. Similar study conducted in Indonesia, planted unit macrophytes *T. latifolia* and *Commelina benghalensis* showed removal efficiency of *E-coli* of 52 % which is less than to what was obtained in this study[11]. Figure 15 below shows RE of TC, FC and *E-coli* in HSSFCW at Excella school in Kigali.

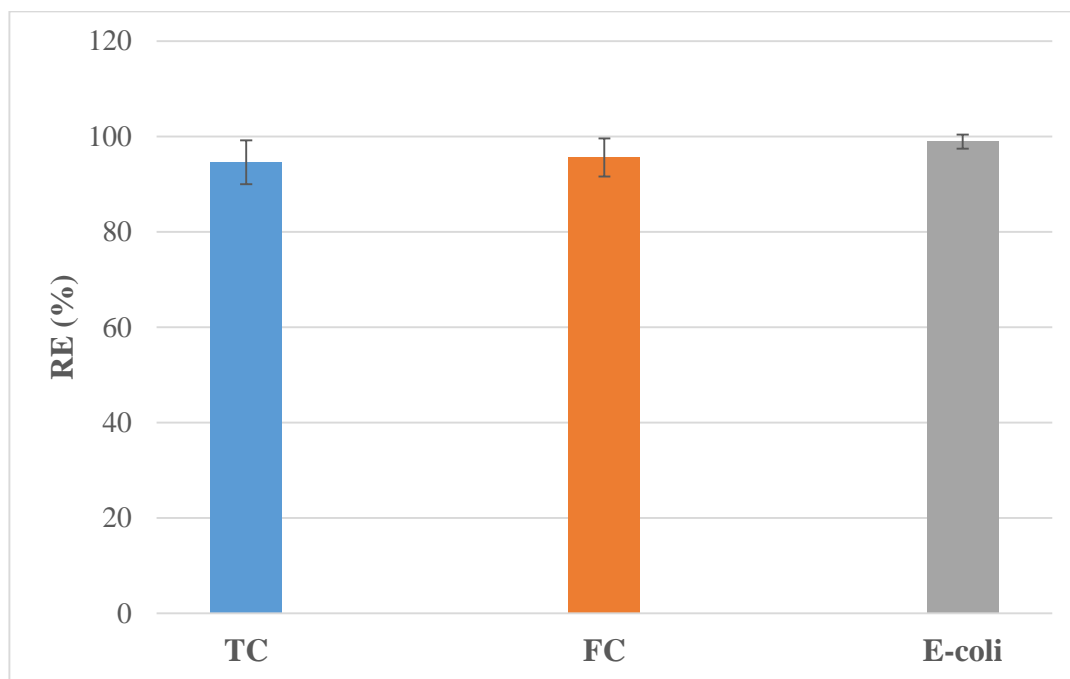


Figure 16: RE of TC, FC and *E-coli* in HSSFCW at Excella school in Kigali

4.5 Comparing the effluent from HSSFCWs treating domestic wastewater at Excella School in Kigali with the standards of water for irrigation.

The decline in precipitation has an adverse effect on agriculture. The significance of sustainable water use acquiring more and more attention as a result of the growing demand for irrigation around the world in order to increase crop yields [61]. Wastewater is effectively disposed of by irrigation, which serves as both disposal and use[26].

The use of wastewater for irrigation can result in significant reductions in both the amount of fresh water needed to irrigate agricultural crops and the amount of fertiliser needed. As a result, it is a successful means for preserving groundwater and surface water supplies as well as for coping with climate change. Reusing water provides advantages that serve as the main drivers for putting reuse programmes into place, regardless of if the goal is to regulate nutrients in treated effluent or supplement water supplies. These advantages include increased agricultural output, less energy use for water production, treatment, and distribution, and important environmental advantages including lower nitrogen loads to receiving waters from recycled treated wastewater. Reuse is motivated by the need to address urbanisation and the shortage of water supplies, use resources efficiently, and safeguard the environment and public health [48].

The effluent concentrations of different parameters were compared by the standard of TWW quality for irrigation (RS ISO 20419:2018) and standard of irrigation water characteristics (RS188:2019) as shown in table 18 and 19 below:

Table 10: Comparison of findings with standard of TWW quality for irrigation

Parameter	Good TWW quality^a	Good TWW quality^b	Good TWW quality^c	Findings
BOD (mg/l)	< 10	10 to 50	>50	103
COD (mg/l)	< 50	50 to 80	> 80	127
TSS (mg/l)	< 30	30 to 70	> 70	30
pH	6 to 7.5	7.6 to 8	>8	8.05

Table 11: Comparison of findings with standard of irrigation water characteristics

Characteristics	Degree of restriction of use			Findings
	Non problems	Increasing problems	Severe problems	
pH	< 6.5	6.5-8.4	> 8.4	8.05
TDS (mg/l)	< 450	450-2000	> 2000	1410.4
EC (mmhos/cm)	< 0.75	0.75-3	> 3	2.5

- The average effluent BOD₅ concentration was 103 mg/L and by comparing to BOD₅ standard, it was in the range of good treated water quality c because it was > 50 of standard.
- The average effluent COD concentration was 127 mg/L and by comparing to COD standard, it was in the range of good treated water quality c because it was > 80 of standard.
- The average effluent TSS concentration was 30 mg/L and by comparing to TSS standard, it was in the range of good treated water quality b because it was in the range of 30-70 of standard.
- The average effluent pH concentration was 8.05 and by comparing to pH standard, it was in the range of good treated water quality c because it was >8 of standard. By comparing pH with the RS188:2019, pH was in the range of 6.5-8.4 where to use water having this pH for irrigation is increasing problems.
- The average effluent TDS concentration was 1410.40 mg/L and by comparing to TDS standard, it was in the range of 450-2000 mg/L of standard where to use water having this TDS for irrigation is increasing problems.
- The average effluent electrical conductivity concentration was 2.5 ms/cm and by comparing to electrical conductivity standard, it was in the range of 0.75-3 mmhos/cm of standard where to use water having this electrical conductivity for irrigation is increasing problems.
- As it is mentioned in RS188:2019, When considering the use of effluents for irrigation, their microbial and biochemical properties should be evaluated. these values should then be compared with the public health standards. Therefore, BOD₅, total coliforms, faecal coliforms and E-coli didn't meet the RSB standards for wastewater to be released in the environment. By sum up, the effluent from HSSFCWs treating domestic wastewater at Excella School in Kigali didn't meet the standards of water for irrigation.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

The conclusions obtained from this study are as follows;

- A. Pollutants removal efficiencies in horizontal subsurface flow constructed wetlands treating domestic wastewater at Excella School in Kigali increased as the macrophytes grew.
- B. For organic matters, the average removal efficiencies of BOD₅ and COD in the whole study period were around 54.9 % and 56.8 % respectively.
- C. For pathogens, the average removal efficiency of total coliforms, faecal coliforms and *E-coli* in the whole study period were around 94.58 %, 95.60 % and 98.89% respectively.
- D. The average Biodegradability Index of the effluent was around 0.78. Therefore, this indicated that there is no sustainability of aquatic organisms living in the effluent receiving water bodies.
- E. For nutrients, the average removal efficiencies of total nitrogen and total phosphorus in the whole study period were around 46 % and 47.9 % respectively.
- F. The effluent from horizontal subsurface flow constructed wetlands treating domestic wastewater at Excella School in Kigali didn't meet the standards of water for irrigation.
- G. Generally, the removal efficiencies of the pollutants were not high especially for nutrients and organic matter due to the fact that the wetlands macrophytes were still growing and macrophytes are very important in removing the pollutants, small part of wetlands is where macrophytes grew. In addition to this, it seems like the slope of the CWs is greater than one 1 which reduce the retention time of wastewater especially at the side of the inlet of the wetlands, therefore, reduce macrophytes growth rate and pollutants RE.

According to this study, the following recommendations are elaborated:

- A. Inspecting effluent quality regularly by routine analysis of important parameters such as total and faecal coliforms, *E- coli*, biological oxygen demand, nutrients and chemical oxygen demand.
- B. To introduce new microorganisms from a good working constructed wetlands to reduce effluent biodegradable matter to meet standard.
- C. To achieve high removal efficiency of pollutants, the wetlands parts which doesn't have macrophytes which was not growing well must be replaced and old macrophytes harvesting plan must be considered.
- D. Further study is required to evaluate the removal efficiency of others pollutants which were not covered in this study and to study how to improve the pollutants removal efficiency.
- E. Trained staff to be in charge of monitoring, maintenance and operation of the system should be hired.
- F. To protect the soil erosion from the whole sides to enter in CWs because it can reduce the performance of the CWs and ensure the continuous flow and equal distribution of influent in all basins of the CWs.

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APPENDICES

Appendix 1: Results of organic matter Removal

Table 1: RE of BOD₅ in HSSFCWs 1 and 2 at Excella School in Kigali.

Sampling date	Wetland 1			Wetland 2		
	Influent (mg/L)	Effluent (mg/L)	RE (%)	Influent (mg/L)	Effluent (mg/L)	RE (%)
27-10-22	220	120	45	-	-	-
11-11-22	217.4	108.5	50	217.4	115	47
25-11-22	213.4	117	45	213.4	108	49
08-12-22	231	115	50	-	-	-
22-12-22	190	86	55	-	-	-
05-01-23	175	70	60	-	-	-
19-01-23	226	104	54	226	126	44
03-02-23	211	79	62.6	211	105	50
17-02-23	220	70	68	-	-	-
02-03-23	210	65	69	-	-	-
Mean ± SD	209.4± 16.9	93.5± 21.7	55.9±8.8	217±6.6	113.5±9.3	47.5±2.6

Table 2: Average RE of BOD₅ in HSSFCWs at Excella School in Kigali.

Sampling date	Influent (mg/L)	Effluent (mg/L)	RE (%)
27-10-22	220	120	45.5
11-11-22	217.4	111.8	48.6
25-11-22	213.4	112.5	47.3
08-12-22	231	115	50.2
22-12-22	190	86	54.7
05-01-23	175	70	60
19-01-23	226	115	49.1
03-02-23	211	92	56.4
17-02-23	220	70	68.2
02-03-23	210	65	69
Mean ± SD	211.4± 16.9	95.7±21.7	54.9±8.5

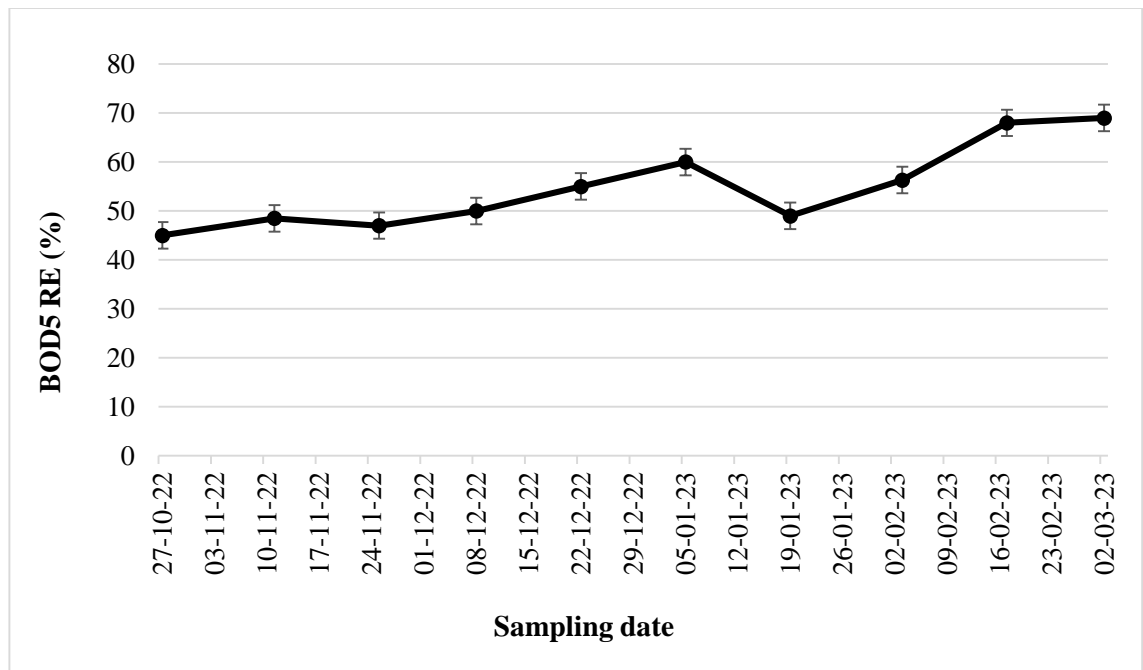


Figure 1: RE of BOD₅ in HSSFCWs at Excella School in Kigali

Table 3: RE of COD in HSSFCWs 1 and 2 at Excella School in Kigali

Sampling date	Wetland 1			Wetland 2		
	Influent (mg/L)	Effluent (mg/L)	RE (%)	Influent (mg/L)	Effluent (mg/L)	RE (%)
27-10-22	282	136.6	52	-	-	-
11-11-22	293.5	125.5	57	293.5	135	54
25-11-22	276.5	131.3	53	276.5	127	54
08-12-22	315	170	46	-	-	-
22-12-22	260	110	58	-	-	-
05-01-23	250	112	55	-	-	-
19-01-23	277.5	122	56	277.5	145	48
03-02-23	295	102	65	295	127	57
17-02-23	315	107	66	-	-	-
02-03-23	281	85	70	-	-	-
Mean ± SD	284.6±21	120.1±23.1	57.8±7.3	285.6±10	133.5±8.5	53.3±3.8

Table 4: Average RE of COD in HSSFCWs at Excella School in Kigali

Sampling date	Influent (mg/L)	Effluent (mg/L)	RE (%)
27-10-22	282	136.6	51.6
11-11-22	293.5	130.3	55.6
25-11-22	276.5	129.2	53.3
08-12-22	315	170	46
22-12-22	260	110	57.7
05-01-23	250	112	55.2
19-01-23	277.5	133.5	51.9
03-02-23	295	114.5	61.2
17-02-23	315	107	66
02-03-23	281	85	69.8
Mean ± SD	284.6±21	122.8±22.7	56.8±7.1

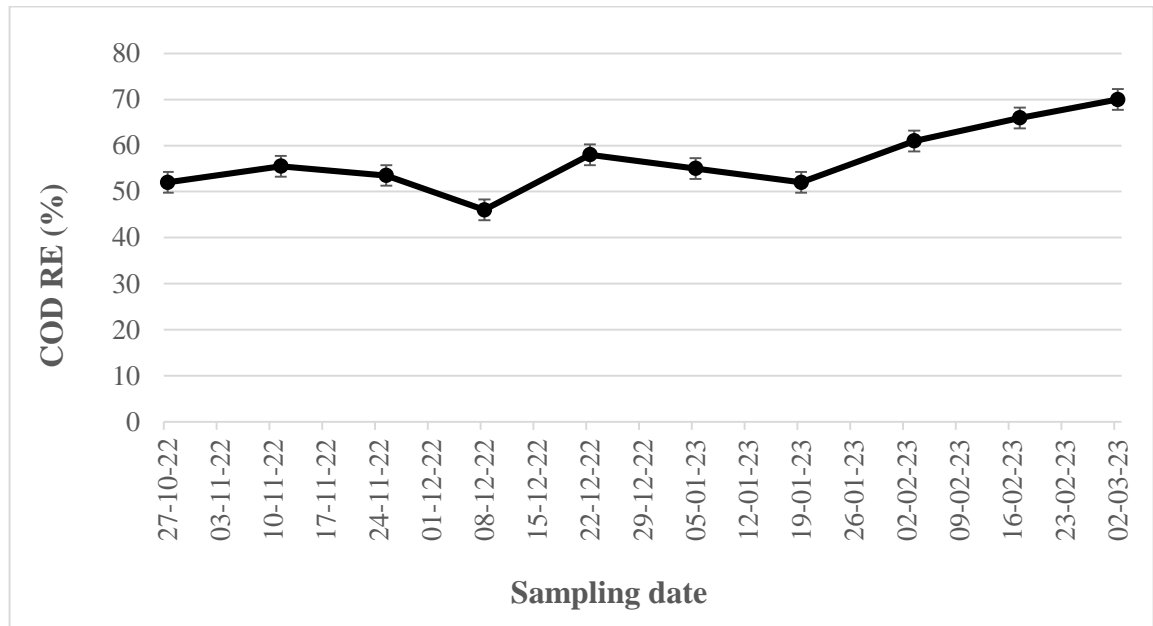


Figure 2: RE of COD in HSSFCWs at Excella School in Kigali

Appendix 2: Results of Biodegradability Index (BI)

Table 1: BI for HSSFCWs 1 and 2 at Excella school in Kigali.

Sampling date	BI for influent	BI for wetland 1 effluent	BI for wetland 2 influent	BI for wetland 2 effluent
27-10-22	0.71	0.88	-	-
11-11-22	0.74	0.86	0.74	0.85
25-11-22	0.77	0.89	0.77	0.85
08-12-22	0.73	0.68	-	-
22-12-22	0.73	0.78	-	-
05-01-23	0.70	0.63	-	-
19-01-23	0.81	0.85	0.81	0.87
03-02-23	0.72	0.77	0.72	0.83
17-02-23	0.70	0.65	-	-
02-03-23	0.75	0.76	-	-
Mean ± SD	0.74± 0.04	0.78±0.1	0.76±0.04	0.85±0.02

Table 2: Average BI of effluent from HSSFCWs at Excella School

Sampling date	BI for influent	BI for effluent
27-10-22	0.71	0.88
11-11-22	0.74	0.86
25-11-22	0.77	0.87
08-12-22	0.73	0.68
22-12-22	0.73	0.78
05-01-23	0.70	0.63
19-01-23	0.81	0.86
03-02-23	0.72	0.8
17-02-23	0.70	0.65
02-03-23	0.75	0.76
Mean ± SD	0.74± 0.04	0.78±0.1

Appendix 3: Results of Nutrients Removal

Table 1: RE of TN in HSSFCWs 1 and 2 at Excella School in Kigali

Sampling date	Wetland 1			Wetland 2		
	Influent (mg/L)	Effluent (mg/L)	RE (%)	Influent (mg/L)	Effluent (mg/L)	RE (%)
27-10-22	2	1.2	40	-	-	-
11-11-22	2.35	1.3	45	2.35	1.7	28
25-11-22	2.1	1.1	46	2.1	1	54
08-12-22	2	1.4	30	-	-	-
22-12-22	1.8	1	44	-	-	-
05-01-23	3	2.1	30	-	-	-
19-01-23	1.8	0.9	50	1.8	1	44
03-02-23	3	1.2	60	3	1.6	47
17-02-23	2	0.7	65	-	-	-
02-03-23	4.4	1.6	64	-	-	-
Mean ± SD	2.4 ± 0.8	1.3 ± 0.4	47.4 ± 12.6	2.3 ± 0.5	1.3 ± 0.4	43.3 ± 11

Table 2: Average RE of TN in HSSFCWs at Excella School in Kigali

Sampling date	Influent (mg/L)	Effluent (mg/L)	RE (%)
27-10-22	2	1.2	40
11-11-22	2.35	1.5	36.2
25-11-22	2.1	1.05	50
08-12-22	2	1.4	30
22-12-22	1.8	1	44.4
05-01-23	3	2.1	30
19-01-23	1.8	0.95	47.2
03-02-23	3	1.4	53.3
17-02-23	2	0.7	65
02-03-23	4.4	1.6	63.6
Mean ± SD	2.4 ± 0.8	1.3 ± 0.4	46 ± 12.4

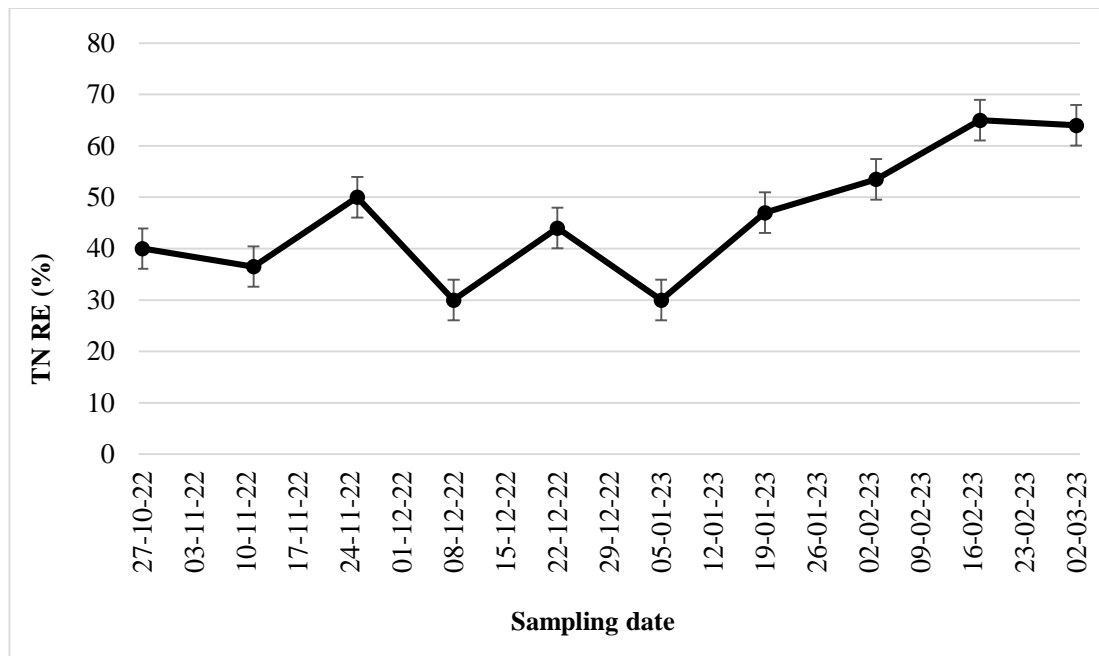


Figure 1: RE of TN in HSSFCWs at Excella School in Kigali

Table 3: RE of TP in HSSFCWs 1 and 2 at Excella School in Kigali.

Sampling date	Wetland 1			Wetland 2		
	Influent (mg/L)	Effluent (mg/L)	RE (%)	Influent (mg/L)	Effluent (mg/L)	RE (%)
27-10-22	5.07	2.5	51	-	-	-
11-11-22	5.17	3.42	34	5.17	4.1	21
25-11-22	6.8	3.2	53	6.8	4.6	33
08-12-22	5	2.9	42	-	-	-
22-12-22	7	3.2	54	-	-	-
05-01-23	6.4	3.9	39	-	-	-
19-01-23	7.6	3.9	49	7.6	3.8	50
03-02-23	5.3	2.5	53	5.3	2.4	55
17-02-23	5.8	2.4	59	-	-	-
02-03-23	3.6	1.4	61	-	-	-
Mean ± SD	5.8±1.2	2.9±0.8	49.5±8.7	6.2±1.2	3.7±0.9	39.8±15.6

Table 4: Average RE of TP in HSSFCWs at Excella School in Kigali

Sampling date	Influent (mg/L)	Effluent (mg/L)	RE (%)
27-10-22	5.07	2.5	50.7
11-11-22	5.17	3.76	27.3
25-11-22	6.8	3.9	42.6
08-12-22	5	2.9	42
22-12-22	7	3.2	54.3
05-01-23	6.4	3.9	39.1
19-01-23	7.6	3.85	49.3
03-02-23	5.3	2.45	53.8
17-02-23	5.8	2.4	58.6
02-03-23	3.6	1.4	61.1
Mean ± SD	5.8±1.2	3±0.8	47.9±10.2

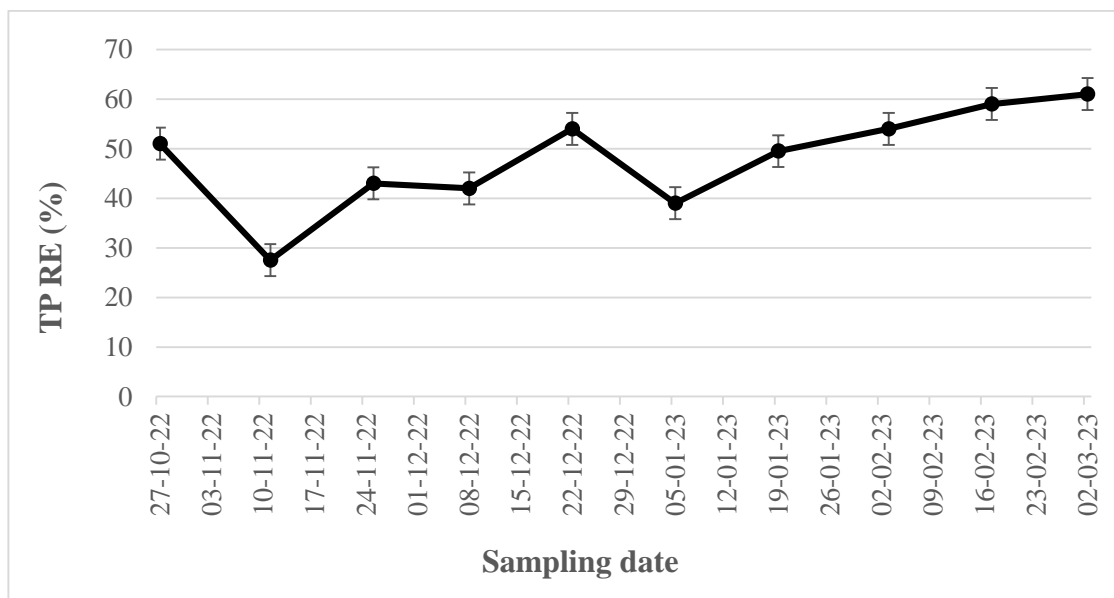


Figure 2: RE of TP in HSSFCWs at Excella School in Kigali

Appendix 4: Results of Pathogens removal

Table 1: RE of TC in HSSFCWs 1 and 2 at Excella School in Kigali

Sampling date	Wetland 1			Wetland 2		
	Influent	Effluent	RE	Influent	Effluent	RE
	(10 ³ CFU/100ml)	(10 ³ CFU/100ml)	(%)	(10 ³ CFU/100ml)	(10 ³ CFU/100ml)	(%)
27-10-22	840	2.6	99.7	-	-	-
11-11-22	333.25	3.7	99	333.25	1.8	99
25-11-22	88.375	2.65	97	88.375	11.4	87
08-12-22	291	3.5	99	-	-	-
22-12-22	17.5	2.2	87	-	-	-
05-01-23	9.5	0.1	99	-	-	-
19-01-23	24.05	2.3	90	24.05	0.7	97
03-02-23	12	1.1	91	12	1.5	88
17-02-23	90	3.5	96	-	-	-
02-03-23	16	1.5	91	-	-	-
Mean	172.168	2.315	94.9	114.419	3.85	92.8

Table 2: RE of TC in HSSFCWs at Excella School in Kigali

Sampling date	Influent (10 ³ CFU/100ml)	Effluent (10 ³ CFU/100ml)	RE (%)
27-10-22	840	2.6	99.7
11-11-22	333.25	2.75	99.2
25-11-22	88.375	7.025	92.1
08-12-22	291	3.5	98.8
22-12-22	17.5	2.2	87.4
05-01-23	9.5	0.1	98.9
19-01-23	24.05	1.5	93.8
03-02-23	12	1.3	89.2
17-02-23	90	3.5	96.1
02-03-23	16	1.5	90.6
Mean	172.168	2.598	94.58

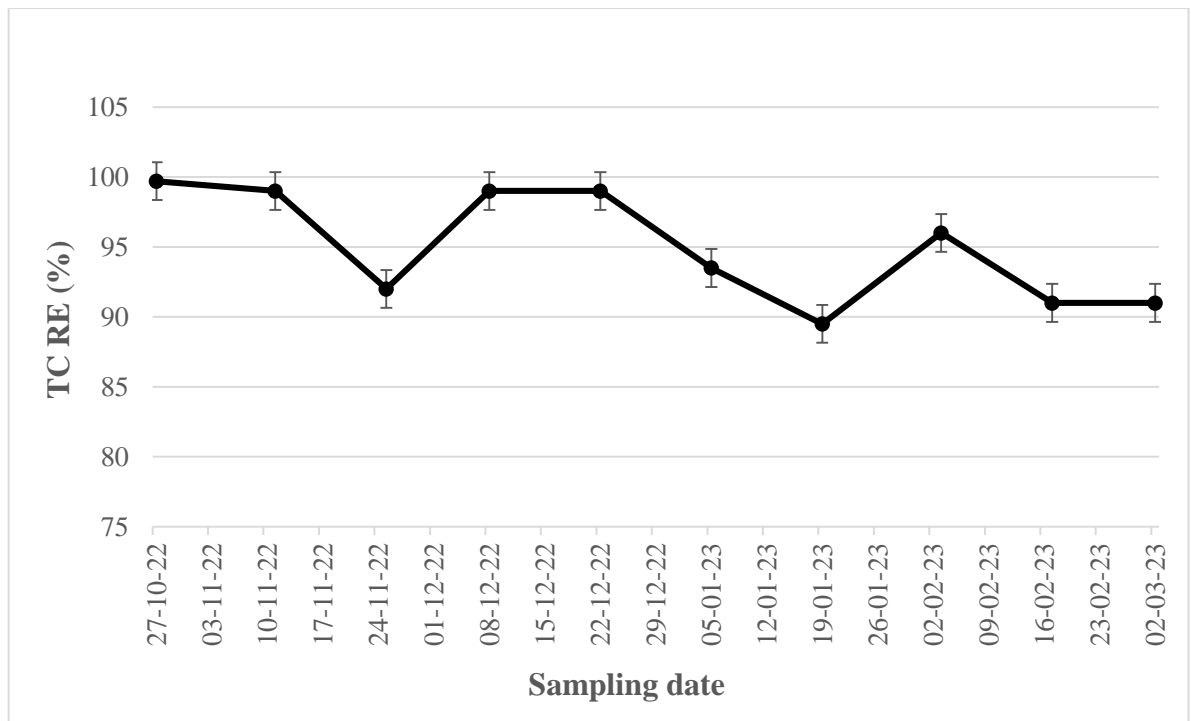


Figure 1: RE of TC in HSSFCWs at Excella School in Kigali

Table 3: RE of FC in HSSFCWs 1 and 2 at Excella School in Kigali.

Sampling date	Wetland 1			Wetland 2		
	Influent (10 ² CFU/100ml)	Effluent (10 ² CFU/100ml)	RE (%)	Influent (10 ² CFU/100ml)	Effluent (10 ² CFU/100ml)	RE (%)
27-10-22	640	1.3	99.8	-	-	-
11-11-22	25.5	1.3	95	25.5	0	100
25-11-22	268.88	3.7	99	268.88	11	96
08-12-22	532	21	96	-	-	-
22-12-22	85	8	91	-	-	-
05-01-23	25	0	100	-	-	-
19-01-23	22	0	100	22	1	95
03-02-23	70	2	97	70	7	90
17-02-23	350	45	87	-	-	-
02-03-23	21	0.75	96	-	-	-
Mean	203.94	8.31	96.1	96.60	4.75	95.3

Table 4: Average RE of FC in HSSFCWs at Excella School in Kigali

Sampling date	Influent (10^{^2} CFU/100ml)	Effluent (10^{^2} CFU/100ml)	RE (%)
27-10-22	640	1.3	99.8
11-11-22	25.5	0.65	97.5
25-11-22	268.88	7.35	97.3
08-12-22	532	21	96.1
22-12-22	85	8	90.6
05-01-23	25	0	100
19-01-23	22	0.5	97.7
03-02-23	70	4.5	93.6
17-02-23	350	45	87.1
02-03-23	21	0.75	96.4
Mean	203.94	8.91	95.60

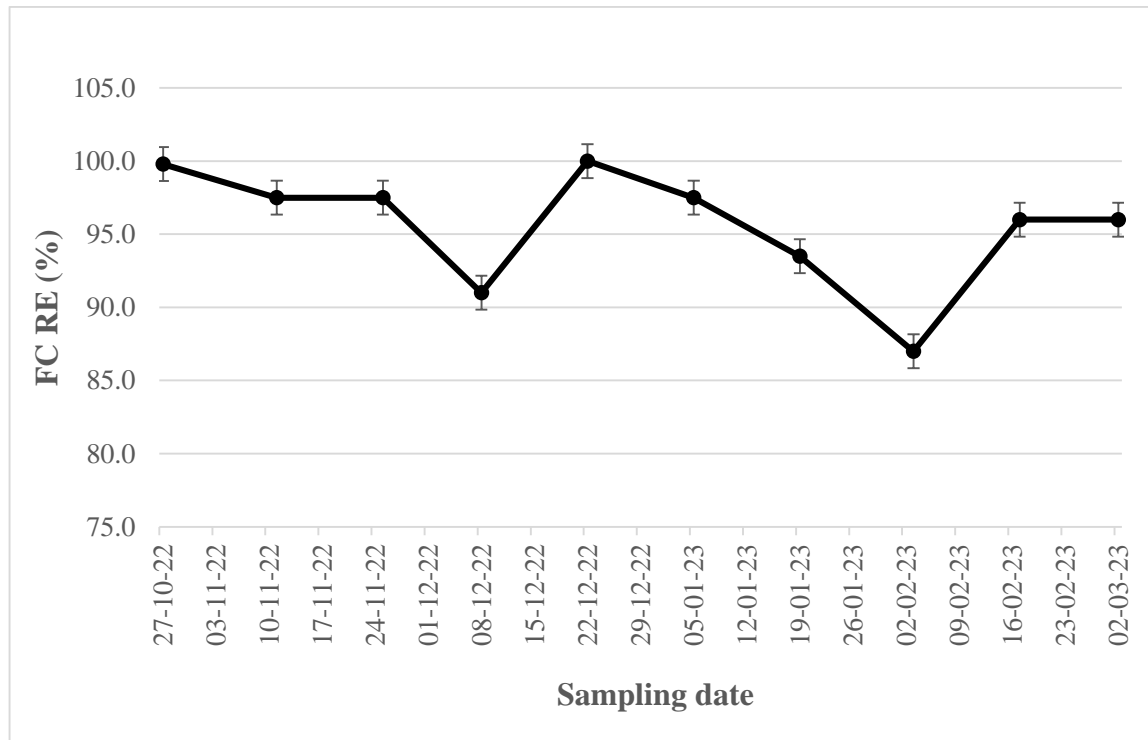


Figure 2: RE of FC in HSSFCWs at Excella School in Kigali

Table 5: RE of *E-coli* in HSSFCWs 1 and 2 at Excella School in Kigali.

Sampling date	Wetland 1			Wetland 2		
	Influent (10 ² CFU/100ml)	Effluent (10 ² CFU/100ml)	RE (%)	Influent (10 ² CFU/100ml)	Effluent (10 ² CFU/100ml)	RE (%)
27-10-22	76	0	100	-	-	-
25-11-22	25.78	0.75	97	25.78	0.9	97
08-12-22	120	0.9	99	-	-	-
22-12-22	26.5	0	100	-	-	-
19-01-23	6	0	100	6	0	100
03-02-23	14	1	93	14	0	100
17-02-23	110	1.5	99	-	-	-
02-03-23	1.6	0	100	-	-	-
Mean	47.49	0.52	98.50	15.26	0.30	99

Table 6: Average RE of *E-coli* in HSSFCWs at Excella School in Kigali

Sampling date	Influent (10 ² CFU/100ml)	Effluent (10 ² CFU/100ml)	RE (%)
27-10-22	76	0	100
25-11-22	25.78	0.825	96.8
08-12-22	120	0.9	99.3
22-12-22	26.5	0	100
19-01-23	6	0	100
03-02-23	14	0.5	96.4
17-02-23	110	1.5	98.6
02-03-23	1.6	0	100
Mean	47.49	0.47	98.89

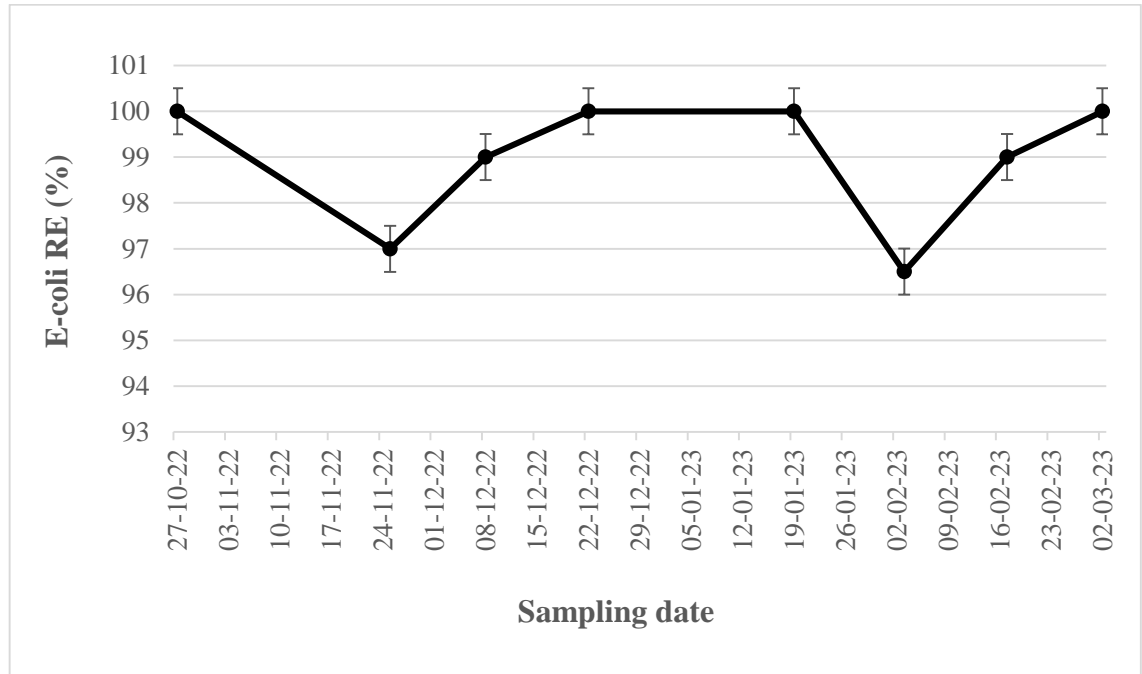


Figure 3: RE of *E-coli* in HSSFCWs at Excella School in Kigali

Appendix 5: Results of other tested parameters

Table 1: Total Suspended Solids (TSS)

Sampling date	Wetland 1			Wetland 2		
	Influent (mg/L)	Effluent (mg/L)	RE (%)	Influent (mg/L)	Effluent (mg/L)	RE (%)
27-10-22	103	41	60	-	-	-
11-11-22	160.5	17	89	160.5	32	80
25-11-22	339.6	52.8	84	339.6	17	95
08-12-22	170	31.5	81	-	-	-
22-12-22	315	50	84	-	-	-
05-01-23	186	23	88	-	-	-
19-01-23	170.5	25	85	170.5	21	88
03-02-23	260	35	87	260	27	90
17-02-23	420	38	91	-	-	-
02-03-23	350	40	89	-	-	-
Mean	247.5	35.3	83.8	232.7	24.3	88.3

Table 2: pH

Sampling date	Wetland 1		Wetland 2	
	Influent	Effluent	Influent	Effluent
27-10-22	7.78	8.56	-	-
11-11-22	7.72	7.81	7.72	8.35
25-11-22	7.9	8	7.9	8.09
08-12-22	7.8	8	-	-
22-12-22	7.9	8.2	-	-
05-01-23	8.5	7.7	-	-
19-01-23	8	8	8	7.68
03-02-23	7.87	8.03	7.87	8.35
17-02-23	7.7	7.9	-	-
02-03-23	7.6	7.7	-	-
Mean	7.88	7.99	7.87	8.12

Table 3: Turbidity

Sampling date	Wetland 1			Wetland 2		
	Influent (NTU)	Effluent (NTU)	RE (%)	Influent (NTU)	Effluent (NTU)	RE (%)
27-10-22	322	40.6	87	-	-	-
11-11-22	256.25	32.7	87	256.25	47.1	81
25-11-22	529.1	56.1	89	529.1	44.1	99
08-12-22	415	31	93	-	-	-
22-12-22	350	24	93	-	-	-
05-01-23	374	19	95	-	-	-
19-01-23	202.5	29	86	202.5	15	93
03-02-23	280	35	88	280	47.5	83
17-02-23	350	48	86	-	-	-
02-03-23	240	30	88	-	-	-
Mean	331.89	34.54	89.20	316.96	38.43	89.00

Table 4: Total Dissolved Solids (TDS)

Sampling date	Wetland 1			Wetland 2		
	Influent (mg/L)	Effluent (mg/L)	RE (%)	Influent (mg/L)	Effluent (mg/L)	RE (%)
27-10-22	2184	1792	18	-	-	-
11-11-22	3465	2335	33	3465	1270	63
25-11-22	3193.8	2126.5	33	3193.8	1057	67
08-12-22	3513	1761	50	-	-	-
22-12-22	4500	1450	68	-	-	-
05-01-23	2610	1065	59	-	-	-
19-01-23	2450	1136	54	2450	1100	55
03-02-23	3150	1400	56	3150	1270	60
17-02-23	3780	1300	66	-	-	-
02-03-23	4350	2100	52	-	-	-
Mean	3319.59	1646.55	48.90	3064.72	1174.25	61.25

Table 5: Electrical Conductivity (EC)

Sampling date	Wetland 1			Wetland 2		
	Influent (ms/cm)	Effluent (ms/cm)	RE (%)	Influent (ms/cm)	Effluent (ms/cm)	RE (%)
27-10-22	5.62	2.93	48	-	-	-
11-11-22	5.9	3.87	34	5.9	2.1	64
25-11-22	5.8	3.9	33	5.8	2	66
08-12-22	6	3.1	48	-	-	-
22-12-22	5.5	3	43	-	-	-
05-01-23	4.8	2.9	40	-	-	-
19-01-23	3.5	2.43	31	3.5	1.7	51
03-02-23	5.77	2.7	53	5.77	2.1	64
17-02-23	6.1	3	51	-	-	-
02-03-23	5.8	2.5	57	-	-	-
Mean	5.48	3.03	43.80	5.24	1.98	61.25

Table 6: Temperature

Sampling Date	Wetland 1		Wetland 2	
	Influent (°C)	Effluent (°C)	Influent (°C)	Effluent (°C)
27-10-22	23	22.5	-	-
11-11-22	22.1	22.8	22.1	21.5
25-11-22	22.7	22.4	22.7	23
08-12-22	23.1	22.5	-	-
22-12-22	22.7	22.4	-	-
05-01-23	23.2	23.4	-	-
19-01-23	22.5	22.4	22.5	23
03-02-23	23.5	23.1	23.5	21.5
17-02-23	22.5	22.7	-	-
02-03-23	22.2	22.5	-	-
Mean	22.7	22.7	22.7	22.3

Appendix 6: Photos of HSSFCWs treating domestic wastewater at Excella School.

