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SCHOOL OF SCIENCE

Evaluation of nutrients removal and typologies for successful operation and maintenance for hybrid natural pond treating municipal wastewater in Kigali

A Dissertation submitted in partial fulfilment of the requirements for the degree of Master (MSc) of Science in Environmental Chemistry

By

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DECLARATION

I, TUYISENGE Ernest, declare that this Dissertation is the result of my own work and has not been submitted to any other degree at University of Rwanda or any other institution.

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Date…. /………/2022

I, Christian SEKOMO BIRAME declare the approval submission of the dissertation for examination

Signature: ……………………….

Date:………./………/2022

DEDICATION

I dedicate my work:

To my Father NZABAHIMANA Laurien

To my mother NYIRANKERA Marceline

To my sisters and brothers

For their help, support and encouragement

To the Almighty God

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ABSTRACT

The increase of population, urbanization and industrialization in Rwanda lead to the production of huge amount of wastewater. Sanitation is needed to save human health and the environment, as well as for long-term development. Poor sanitation and wastewater management methods, on the other hand, have damaged the ecosystem and most fresh water sources in developing countries including Rwanda resulting in waterborne diseases. Municipal wastewater contains nutrients and pathogens which may have negative impact on environment and human life. Natural treatment systems such as constructed wetlands and ponds are utilized to treat municipal wastewater also are highly efficiency when they are properly maintained. In Rwanda there is few natural systems for treating wastewater but there are no appropriate management mechanisms for those treatment systems in order to keep them in a sustainable manner. The objectives of this research were: (1) Evaluate the nutrients removal efficiencies and limitation of the hybrid natural pond treating municipal wastewater. (2) Evaluate the mechanisms of nutrients and pathogen removal in the systems based on their design and local climate and (3) Assess the appropriate methods for the system operation and maintenance based on local knowledge and technology.

The grab samples were taken for four sampling points of Nyarutarama natural hybrid pond every week in a period of six weeks. During the monitoring period, temperature, pH, DO, and EC were measured on-site, nutrients and pathogens were determined in the laboratory and the key informant interviews were conducted.

During the monitoring period of six weeks, the average removal efficiencies of the primary pond, secondary pond and CW: NH_4-N (14%, 20% and 54%), NO_2-N (28%, 38% and 45%), NO_3-N (27%, 38% and 48%), TN (14%, 19% and 27%), PO_4-P (38%, 46% and 57%), TP(39%, 46% and 56%), TC(36%, 83% and 58%), FC(43%, 81% and 57%) and E. Coli (42%, 90% and 57%) respectively.

The results showed that the pathogens were highly removed but the effluent did not comply to the standards. Preliminary treatment, awareness raising for willingness to pay, improvement of the treatment systems area for their valorization and permanent and trained staffs to oversee the system operation and maintenance, these methods can be applied for sustainable management of natural treatment systems in a highly urban region.

Key words: Municipal wastewater, Constructed wetland, nitrification, nutrient removal, Awareness.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BOD: Biochemical Oxygen Demand

CFU: Colony Forming Unit.

CW: Constructed Wetland

DO: Dissolved Oxygen

EC: Electrical Conductivity

FC: Feacal Coliform

HSSFCW: Horizontal Subsurface Flow Constructed Wetland

IUCN: International Union for Conservation of Nature

pH: Potential of Hydrogen

RE: Removal Efficiency

RSB: Rwanda Standard Board.

SDG: Sustainable Development Goals

SFCW: Surface Flow Constructed Wetland

SS: Suspended Solid

TC: Total coliform

TN: Total Nitrogen

TP: Total Phosphorus

VFCW: Vertical Flow Constructed Wetland

UN: United Nations

WASAC: Water and sanitation Corporation

WHO: World Health Organization

WSP: Waste Stabilization Pond

WWTP: Wastewater Treatment Plant

Chapter 1: INTRODUCTION

1.1. Background and Justification

Access to potable water and hygiene facilities are one of the most pressing issues facing the developing countries due to the globe's population growth. In fact, the United Nations estimates that about one billion people in the world do not get potable water and nearly 2.2 billion do not have access to primary hygiene [1]. The sustainable control of water resources is a crucial all over the world [2]. It has been evaluated that, by 2025, 1 800 million people will live in areas with deficient water, also two-thirds of the global population will be stressed [3].

Rwanda is a landlocked country found in the Great Lakes zone of East Africa. It is bordered by Uganda in the North, Burundi in the South, Tanzania in the East, and the Democratic Republic of the Congo in the West. This country has a total surface of 26,338 km^2, with population density of 399.3 inhabitants per Km^2 in 2012 with the future population density is projected to be 618.9 inhabitants per Km^2 in 2032 [4]. This increasing rate of populations needs to safeguard the available water sources by implementing the sewage treatment systems and increasing sanitation facilities.
Rwandan data shows that a large percentage of households (53% in rural and 39% in urban) still have to walk long distances to get to a better supply of water, and 36% of all households do not have access to improved sanitation. The most affected persons in both water and sanitation are those in the lowest wealth quintile and those who are difficult to reach, a type of inequality that must be addressed. Rwanda also lacks effective performance monitoring systems and has yet to establish defined funding sources and long-term water sanitation and hygiene policies [5, 6].

In many developing countries, there is lack of water and sanitation facilities. The release of untreated sewage can cause many diseases and environmental issues. In Rwanda, except in some newly constructed real estate, the main practices for disposing off domestic wastewater are pit latrines, household septic tanks followed by the direct discharge of wastewater into bushes, rivers or wetlands and only few hotels, hospitals and few small residential areas in Rwanda have wastewater treatment systems [7].

A recent study from the Rwanda Ministry of Natural Resources, aiming to generate data that will contribute to monitor and report on Environment and Climate Change as well as Sustainable Development Goals (SDGs), has shown that only 4 water bodies out of 27 have at least 80% of monitored parameters meeting with the targeted values [8].

From this study, parameter like Escherichia coli was almost always out of the acceptable range for surface water quality, and this was attributed to increased water pollution activities due to surface runoff, domestic and industrial wastewater. Thus, like SDGs highlight "the world needs to change the method it manages its water resources, also upgrade water and associated sanitation services" [9].
In order to overcome the problem of untreated wastewater, the government of Rwanda in 2017 proposed a project of building centralized wastewater treatment plant in Kigali city, Nyarugenge district which will have the capacity of 120,000 populations equivalent, i.e., approximately 10% of the population of Kigali city.

The centralized wastewater treatment systems are effective in the presence of pecuniary investments with the sanitation chains. The government of Rwanda effort need to be supported by other sustainable and economical solutions of wastewater treatment systems which also consider the wastewater valorization and simple, but effective, operation methods by local communities and also implement other systems which are eco-friendly technology. Constructed wetlands (CWs) are considered as the greatest systems using sustainable solutions, especially for small communities [10].

Actually, considering their low cost, easy operation and maintenance as well as their use of natural process, CWs have been reported by different authors as proven sustainable natural wastewater treatment systems with high potential for application in developing countries [11–13]. In Rwanda, considering the lack of centralized wastewater systems, the use of on-site systems including constructed wetlands has started to emerge slowly in this decade. The 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. The currently known systems/institutions that has constructed wetlands as part of their components include 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 maintenance and least impact on the environment, CWs will likely be used in the planned green model villages/cities in Rwanda. Natural treatment systems such as constructed wetland or ponds are considered to be inexpensive and sustainable. This research evaluated the nutrients and pathogens removal in hybrid pond for treating municipal wastewater and proposed the possible proper sustainable management methods of the natural wastewater treatment systems.

1.2 Problem statement

Domestic wastewater contains nutrients (nitrogen and phosphorus containing compounds), nitrogen compounds come from urine and phosphorus compounds come from the use of detergents that contain phosphate. Wastewater with excess of these nutrients is considered as contaminants. When released into water bodies like lakes, rivers also canal cause oxygen depletion and alterations in their trophic status above the natural state. Domestic wastewater also contains pathogenic microorganisms. The direct discharge of partial or untreated domestic wastewater into the environment my cause major health problems to human. Conventional wastewater technologies are overpriced due to the construction cost, maintenance and mend costs and costs to recruit skilled personnel for careful operation. They include of the collection, transportation, treatment, and discharge of wastewater [14].

In many developing countries, the level of wastewater treatment is insufficient because of the above reason. The implementation of low-cost wastewater treatment technology that can produce effective effluent to meet regulatory standards for domestic wastewater purposes is now the most important challenge in wastewater management in developing countries. The primary goal of wastewater treatment is to prevent disease transmission. Other goals that today's world is concerned about include nutrient recovery, water reuse, and reduced usage of water resources. Conventional treatment systems need to be change into natural ones which are sustainable to promote the conservation of environmental resources to achieve the SDG 6 and SDG 3. Constructed wetlands (CWs) have been used for many years now and considering that the potential application of this eco-technology is enormous in developing countries, the recent review of Diederik on applications of CWs in Africa shows that in several cases the built systems were not so much the constructed wetland technology as such [15].

The major reoccurring problem found in those CWs systems are related to under-dimensioning which results in system overloading and also the wrong operation which is the source of non-compliant effluent concentrations [15]. In addition, it is clear that applications of CWs technology in Africa is under-searched based on the 49 peer-reviewed publications identified in a country-by-country literature search in which only 10 countries in Africa are present where Egypt, Kenya, and Tanzania take the lead in terms of CWs research [15].

Furthermore, it should be noted that the government of Rwanda has recently committed to reuse the treated wastewater effluent for irrigation purposes under the National Determined Contribution to Paris Agreement related to climate change [16]. Lack of appropriate management system of the constructed natural wastewater treatment systems leads them to release the effluent which does not meet the regulator standards, there is a need of awareness for local authorities and people who reside in the region where there are natural wastewater treatment systems for maintenance of those kinds of infrastructure in order to sustain their operation. Also, the study of appropriate reuse of the effluents in various activities is needed depending on the effluent quality.

1.3. Objectives of the research

1.3.1. General objective

The major objective of this study is to evaluate the performance of Nyarutarama hybrid wastewater treatment pond for nutrients and pathogens removal and assess the sustainable methods for its operation and maintenance.

1.3.2. Specific objectives

1. Evaluate the nutrients removal efficiencies and limitation of the hybrid natural pond treating municipal wastewater.
2. Evaluate the mechanisms of nutrients and pathogen removal based on the system design and local climate.
3. Assess the appropriate methods for the system operation and maintenance based on local knowledge and technology.

1.4. Research questions

1. How is the removal efficient of nutrients in the hybrid natural wastewater treatment pond receiving municipal wastewater?
2. How is the removal efficiency of pathogens in the system?
3. What are the existing challenges/gaps in the management of the natural wastewater treatment systems in the study area?
4. Which methods can be applied for sustainable operation and maintenance of such systems in a highly growing urban?

1.5. Relevance of research

This research project was contributed in minimizing water pollution in Rwanda. In particular, this research was helped the global achievement of SDG, goal number 6 to secure accessibility and long-term management of water and hygiene for all, however is in other ways related to several other SDGs, such as SDG, goal number 2 Zero Hunger, regarding to wastewater reuse in agriculture, SDG, goal number 3 health and well-being, concerning to reduce illness from water pollution and SDG, goal number 13 Climate, regarding to reduce energy need for wastewater treatment [17].

In Rwandan context, where various feasibility studies are currently initiated for building and upgrading wastewater treatment plants, this research played a key role in realizing different cost saving opportunities and environmental benefits such as cheap wastewater treatment and wastewater reuse. Agriculture sector requires huge amount of water, reuse of wastewater in that sector will be a good solution because municipal wastewater contains high concentration of nutrients. This source of water has nutrients necessary for plant growth, so by utilizing it, will reduce the price spent on fertilizers. The treated wastewater can also be used in constructions and clean and wash some materials.

In addition, Rwanda has revised in 2021 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.

The good effluent quality and aesthetic of the natural treatment system will be achieved when the proper management system is applied.

1.6 Scope of the work

The structure of this study is summarized as follows, the first chapter described about the water uses and wastewater generated, main issue of discharging untreated municipal wastewater and objectives of this research. Second chapter is concerned on theories and previous research in the field of natural treatment systems (Ponds and constructed wetlands) and their sustainable management. This is followed by the third chapter of methodology which summarized the procedures that carried out in study (study area description, sample collection and analysis). The fourth chapter presents the findings obtained with their discussions. This was indeed tried to clarify fascinating findings on usage and efficiency of natural treatment systems to treat municipal wastewater. The last chapter of conclusion and recommendations is comprised the major output of the research about scientific feasibility natural treatment systems and proposal on the sustainable methods for maintenance and operation natural treatment systems and recommendations on proper management of natural wastewater treatment systems.

Chapter 2: LITERATURE REVIEW

2.1. Characteristics of Wastewater

Wastewater is the kind of water that can cause harmful effect to human in terms of quality. It is comprised of liquid and solid waste released from homes, business houses, industrial plants and agricultural facilities or land. The pollutants from wastewater have different concentrations. Wastewater has three distinct characteristics which are physical, chemical and biological characteristics [18].

2.1.1. Physical parameters

The most important physical characteristics of wastewater are:

***Temperature:** It varies according to the seasons of the years

***Colour:** Normally, wastewater has dark grey or black colour.

***Odor**: It has unpleasant smell.

***Turbidity**: Wastewater is usually highly turbid due to the great content of suspended solids [19].

2.1.2. Nutrients and pathogens determining the quality of wastewater

2.1.2.1. Nitrogen

Nitrogen is a critical component in the production and management of water contamination, mostly for the reasons listed below:

(i) Water pollution

Nitrogen is a very important nutrient for algae, which can cause eutrophication for various water bodies. This reduces the amount of dissolved oxygen consumption in the receiving water body due to the transformation of ammonia to nitrite and there is further oxidation of nitrite to nitrate. Ammonia one of the nitrogen forms is an acute toxic to fish and it is also associated with illnesses such methaemoglobinaemia in the form of nitrate.

(ii) Treatment of wastewater from houses.

Nitrogen is a crucial ingredient for the bacteria that process sewage. Nitrogen and alkalinity are used up during the nitrification processes that can occur in a wastewater treatment system, which convert ammonia to nitrite and nitrite to nitrate. Another process of transforming nitrate to nitrogen gas (denitrification) that can occur in a wastewater treatment plant (WWTP, leads to (a) the conservation of oxygen and alkalinity (when occurring in a manageable way) or (b) the settleable sludge can be destroyed when not under control.

Organic nitrogen and ammonia are the most prevalent forms in raw domestic wastewater. Organic nitrogen compared with amino groups. Urea is the primary source of ammonia, it is directly hydrolyzed and seldom gotten in untreated sewage.

The distribution of ammonia forms according to the pH. Almost all ammonia is the form of ammonium at pH lower than 8, at pH equivalent to 9 there is 50% NH_3 and 50% NH_4^+ but at pH higher than 11 all ammonia is obtained in the form NH_3. As can be seen, the ammonia present is almost completely ionized in the normal pH range, close to neutrality. This has serious environmental implications because free ammonia is toxic to fish even at low concentrations [19–21]. This distribution is also favored by the temperature in wastewater. When the temperature is 25^{o}C, the amount of free ammonia with respect to total ammonia is approximately doubled when compared to 15^{o}C.

2.1.2.2. Phosphorus

Total phosphorus presents in domestic wastewater is in the form of orthophosphates which are mostly come from used detergents, cleaning agents and other chemical products used at home and organic phosphorus come from organic matters [22].

The forms of orthophosphates found in water are as follows: PO_4^{3-}, HPO_4^{2-}, $H_2PO_4^-$, H_3PO_4. The HPO_4^{2-} is the predominant form in domestic wastewater. Phosphorus is used for manufacturing of fertilizers, detergents, and cleaning agents and is found in human and animal waste. All phosphorus found in domestic wastewater, more than 50% come from detergents [23]. Microorganisms able to stabilize organic matter require phosphorus for their growth. Phosphorus is also necessary nutrient for the growth of algae even if at high concentration causes euthrophication to water bodies.

2.1.3. Pathogenic organisms and feacal contamination indicators

(i) Pathogenic organisms

The majority of these organisms play a variety of critical roles, the majority of which are related to the conversion of components in biogeochemical cycles. The kind of these organisms are used in to treat wastewater by biological technology.

Pathogenic organisms are also the source of disease transmitted through the water; this shows that the water is polluted.

(ii) Indicator organisms

Pathogenic organisms are more complicated to be detected in water sample because they are traces.

To detect them requires the huge volumes of the sample. This barrier is overcome by looking for feacal contamination indicator organisms. These organisms are mostly non-pathogenic, but they provide a good indication of whether the water has been polluted by human or animal feces, and thus of its ability to spread diseases. The bacteria of coliform group are selected to be used for this purpose because they have the ability to survive in water than other pathogenic bacteria.

This is significant because coliforms would not be good indicators of faecal contamination if they died faster than pathogenic organisms, and a sample lacking coliforms could still contain pathogens. These applications are for pathogenic bacteria, as other microorganisms can exhibit greater resistance than coliforms.

- The mechanisms used to remove coliforms in wastewater treatment systems are the same as for pathogenic bacteria. This explains that the removal of pathogenic organisms is correlated to that of coliforms.
- The laboratory techniques used to detect coliforms are faster and less expensive compared to those of pathogens

The following are the most commonly used indicators of faecal contamination: Total coliform (TC), Faecal coliform (FC) and Escherichia coli (E. Coli).

2.2. Characteristics of domestic wastewater in Rwanda

Domestic wastewater can be defined as the water released after being used by a community and includes any materials that have been applied to it during that period. It is made up of human waste (feces and urine) mixed with the water used to flush toilets, as well as sullage, which is wastewater from personal washing, laundry, food storage, and kitchen utensil cleaning. It's usually made up of 99.9% water and 0.1% solids [24].

In Rwanda, the sanitation facilities were not enough for all population, there was a use of on-site pit latrines which accounted 96% of population although the use of flush toilets was on 1.4% of population, except 76% of Rwanda's population had access to safe water and the average amount of water consumed was around 20 L/capita/day [25].

The wastewater is controlled by the landholder, primarily through the use of septic tanks and soakaway; but big institutions produce large amount of greywater which may become hard to be controlled by soakaway and septic tanks, as another option they can be reutilized for irrigation purpose due to its nutrient contents needed crops or released in the environment without treating it, even if it may be highly contaminated up to the level overpassed the Rwanda Standard Board's tolerant limits for domestic wastewater discharge.

Table 1: Rwanda Standard Board (2016), contaminant tolerance levels for domestic wastewater discharge [26].

Parameter	**Limits**
TDS, mg/L	< 1500
TSS, mg/L	< 50
Ph	5-9
Total nitrogen (TN), mg/L	< 30
Nitrites (NO_2^-), mg/L	< 2
Nitrates (NO_3^-)	< 20
Total Phosphorus, mg/L	< 5
Feacal coliforms, cfu/100mL	< 400

Untreated domestic wastewater discharge can cause a variety of health and environmental issues. Diseases come from untreated of partially treated wastewater took two – thirds of total ignored tropical diseases (737,000 cases) in Rwanda in 2012, according to the Rwandan Ministry of Health. It is critical in a densely populated area such as Rwanda, it is necessary to treat various kind of wastewater before discharge or reuse of it in order to minimize the human and environmental pollution caused by the wastewater.

2.3. Septic tank

A septic tank is a collection and storage vessel for solid sewage also with liquids. The tank receives raw sewage from the house sewer. Wastewater flows from the house sewer line to the septic vessel where more and less dense solids segregate from the wastewater. Solids which are overweigh than water lodge out forming a sludge layer at the surface of the septic container (as indicated on the figure 1). Substance underweight than water flow to the top of the wastewater forming a scum layer [27].

The sludge and scum are separated by a liquid layer of water containing suspended solids, nutrients, microorganisms, and other pollutants. Anaerobic bacteria start to degrade waste in the sewer, minimizing the volume of collected solid at the sewer surface on 40 – 50% although generating methane, carbon dioxide, water, and reduced sulfur gases [28]. For the well designed and regularly controlled septic tank, the scum and sludge flow with the effluent. The performance of septic tanks is determined by the characteristics of the influent and the tank design. The following are some examples of septic tank removal efficiency: BOD 46–68%, TSS 30–81%, phosphate 20–65%, and fecal coliforms 25–66% [29].

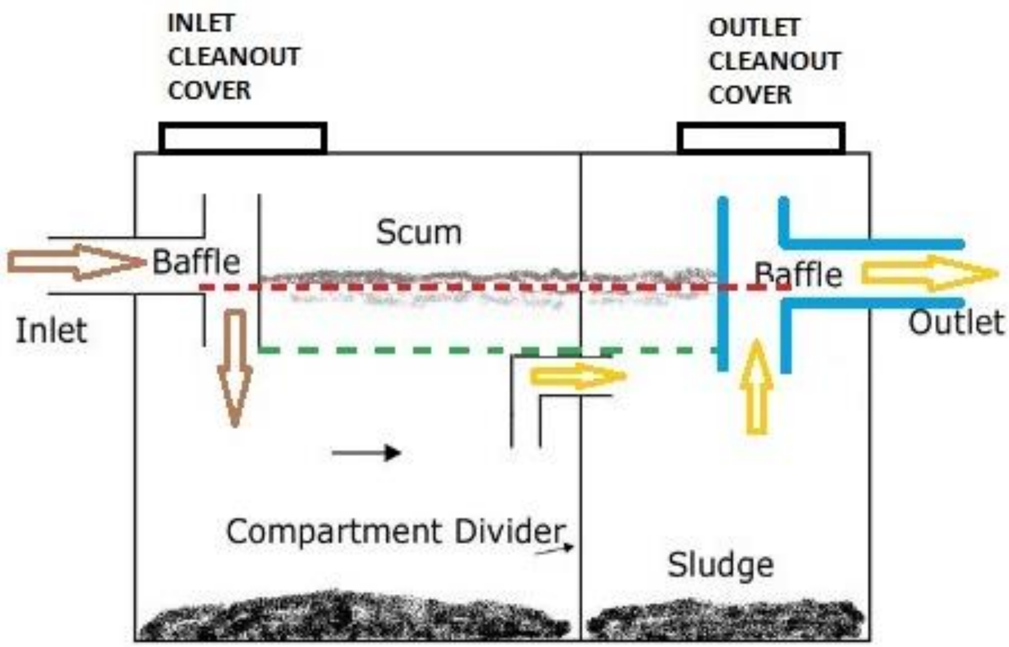

Figure 1: Septic tank [27].

Proper plumbing, tank capacity, and tank dimension are all important design parameters for septic tanks. To prevent short circuiting, a sanitary tee pipe suitable on the inlet sends the influent down in the sewer. Floating scum is prevented from escaping and fouling the wetland or tile field receiving the effluent by a sanitary tee on the outlet. The chamber dividing wall of a two-chamber tank permits liquid free of scum and sludge to travel from the first to the second chamber, and it has ventilation above the liquid level to permit chambers to have the same. After the maximum estimated volume of sludge and scum has formed, enough tank volume is required to ensure that the tank has a minimum of 24-hour fluid retention period for particulate settling. [28].

Septic tank with two chambers is more advantageous than single one because of the lower disturbance give more sedimentation conditions. The slower rate of intake and good design of second chamber improve the effluent quality. In comparison of single and two- chamber septic tank with the same dimensions, the influence of tank size was investigated. The single-chamber tank was said to be better at removing organic and suspended solid matters. The cause was linked to the chambers' surface area and the resulting overflow rate, which has a direct impact on separate sediments [30].

In addition, the higher surface area minimizes the amount of head added to the system by the pump generated by influent flow and reduces the influence on outlet velocity, which, if set too high, could drag colloidal substances away from the tank [31]. Other research, on the other hand, found that two-chamber tanks had greater solids removal efficiency because sediments in single-chamber tanks were resuspended by increasing of bubbles from the anaerobic digestion of the collected solids [32].

The septic tank effluent may look clear, but it contains microorganisms like bacteria as well as nutrients like nitrogen and phosphorous. Further treatment by constructed wetlands is requires in order to reduce the environmental pollution and human diseases.

2.4. Waste stabilization ponds

Waste Stabilization Ponds (WSPs) are defined as the large and shallow basins surrounded by embankments whereby raw wastewater is treated naturally by intervention of bacteria and algae in a pond. WSP components include a single series of anaerobic, facultative, and maturation ponds or multiple series in parallel configurations. WSP systems are made up of either a single series of anaerobic, facultative, and maturation ponds or various series running in parallel. Mostly pond system are used in combination with other systems [33].

2.4.1. Classification of Waste stabilization ponds

2.4.1.1. Anaerobic ponds

The anaerobic ponds are very small arranged in series, and are used for primary treatment rather than producing high-quality effluent. In anaerobic ponds, large concentrations of organic and inorganic particles in wastewater are stabilized, and biological activity takes place in the lack of oxygen. This process produces of methane gas and sulphur-containing malodrous gases. Sedimentation and anaerobic digestion are the processes which minimize the amount of solid particles in raw wastewater. Because anaerobic ponds lack oxygen, they function similarily to unclosed septic tanks[34].

Anaerobic digestion takes place in the pond's sludge, resulting from the conversion of influent organic matter to methane and carbon dioxide, in addition to the release of some soluble by-products into the water column. Anaerobic pond is designed for organic matter removal because at 20°C BOD can be removed approximately 60%. No nutrients removed in anaerobic ponds. Odour, increase in ammonia and sulphide concentrations are the most issues caused by anaerobic ponds [35].

2.4.1.2. Facultative ponds

Facultative ponds are ponds having an aerobic zone not far away surface with gradient to anaerobic condition near the bottom. The main source of oxygen in systems come from algae photosynthesis and the action of wind, however the produced oxygen in not enough to keep up in depth of facultative pond to be full of aerobic condition. Two class of facultative ponds are: Primary and secondary. The primary facultative ponds acquire raw wastewater from the anaerobic pond, whereas the secondary ponds receive settled wastewater effluent from the primary pond [33-35].

2.4.1.2. Maturation ponds

Maturation ponds are defined as simply ponds used to reduce pathogenic microorganisms. They're usually used in series with facultative ponds. The main purpose of this pond is to remove excreted pathogens so that crop watering can be done without restriction. The removal of nutrients also occurred in this kind of ponds [33].

In addition to removing a large percentage of microorganisms, some algae and nutrients can be eliminated by maturation ponds. The bacterial effect of the maturation pond is caused by a combination of natural factors such as solar ultra-violet radiation, high temperature, high pH value, and natural die-off [36].

2.4.2. Advantages and Drawback of WSPs

Advantages of WSPs:

- Easy for designing and building
- Generate small amount of sludge
- Require little money
- High performance when well designed

Drawback of WSPs:

- Ponds necessitate a large amount of land.
- Coldness minimizes the ability of bacteria which leads to large amount of sludge
- Development of mosquito and insects for unharvested macrophytes [35].

2.5.Constructed wetlands

2.5.1. Introduction

Constructed wetlands are artificial system designed to use the natural functions of wetland vegetation to treat wastewater in a controlled way. They can give other benefits such as habitat for wildlife and plants, as well as recreational and aesthetic benefits [37]. They are environmentally technology for treating wastewater in developing countries, however their implementation are not enough due to a lack of technical capacity and awareness [38].

Constructed wetlands are utilized to treat various kind of wastewater such as domestic, industrial and agricultural wastewaters etc. In addition, they can be used to remove nutrients from surface waters which may be at high concentration in order to reach them at the level which cannot harm the environment whenever they are discharged [39] . These natural treatment systems can remove large quantity of nitrogen, phosphorus, and microorganisms from wastewater [40].

In 1989, the Czech Republic built the first full-scale constructed wetland for wastewater treatment. At the end of 1999, approximately 100 constructed wetlands were operational. The majority of these constructed wetlands are horizontal subsurface flow systems intended for secondary treatment of domestic wastewater. Vegetated beds have a lower rate of nutrient removal. The first systems, constructed in the 1970s and soon 1980s, relied heavily on soil materials, which crashed to keep high hydraulic conductivity. This made in increased surface flow and decreased performance [41].

In 1960s the Horizontal constructed wetlands were built by Seidel after ten years Reinhold Kickuth ameliorated them. At the end of 1986, there was a beginning of using some filtration substance in order to guarantee the surface flow [42]. There was a publication of a brief of decade experience these kinds of natural treatment systems were used in the Czech Republic for treating wastewater. One author described that in the Czech Republic was more than 100 constructed wetlands and all are horizontal subsurface flow constructed wetlands designed to treat domestic wastewater [43].

In 1991, there was the construction of first surface flow constructed wetland in Norwegian intended to treat domestic wastewater. In this country there was a use of biofilter which help to ensure the surface flow of water. The removal of nitrogen in Norwegian was about 40 to 60%, the removal of coliforms was very high and their concentration was less than 1000cfu/100ml which met the world health organization discharge for wastewater [44].

The capital costs of subsurface flow constructed wetlands are determined by the cost of bed media as well as the cost of land. Financial management regarding treatment processes should be based on net present value or whole-of-life costs, which contain the cost needed for operation and maintenance of the whole year [45].

2.5.2. Advantages and disadvantages of constructed wetland

This treatment system has many advantages but it has also the disadvantages, some of them are stated below:

* Preservation of natural wetlands, resistance to the variability of environmental conditions,

* No sludge generated and the effluent concentrations of contaminants are low [45].

* Horizontal subsurface flow constructed wetlands (HSSFCW) do not affected highly by change of seasons [46].

* No need of electricity for pumping [47].

*There is a mosquito breed for free water surface flow constructed wetland due to macrophytes[44].

* Need of large land, this limits the implementation of this system in the regions where land is expensive [48, 49].

2.5.3. Types of Constructed wetlands

2.5.3.1. Free water surface flow constructed wetlands (SF CWs)

Free water surface flow constructed wetlands composed of surface water exposed to the atmosphere (20-40 cm deep) and sometimes 20-30 cm of rooting soils, and the flow is expected to be horizontally across a system. Since they include macrophytes which embedded in a soil layer down the wetland and water flows across different parts of the plant such as leaves and stems, they have the appearance of natural wetlands [50].

In SF CWs, water moves above the substrate as well as macrophytes are fixed below water column where aerobic conditions dominate near the surface layer. The water moves in horizontal way across the plant stems also rhizomes and coming together with the top layer of the soil, various parts of the plant and the related biofilms which permit contaminants to be eliminated via different physical, chemical and biological processes. Mosquitos may be developed in SF CWs if the water rest practically in static conditions inside the system due to incorrect design or building. The removal of suspended solids (SS) and biochemical oxygen demand (BOD) is good, removal of nitrogen (N) and pathogens is satisfactory, however the removal of phosphorus (P) is generally shorten in this type of constructed wetland [51,52].

SF CWs was designed for primary and secondary treatment of municipal effluents, but primarily for polishing treated effluents, storm water and highway runoff, and for agricultural effluents [51,53]. This type of constructed wetland requires large surface area with respect to other wetland types but it has the appearance of natural wetlands.

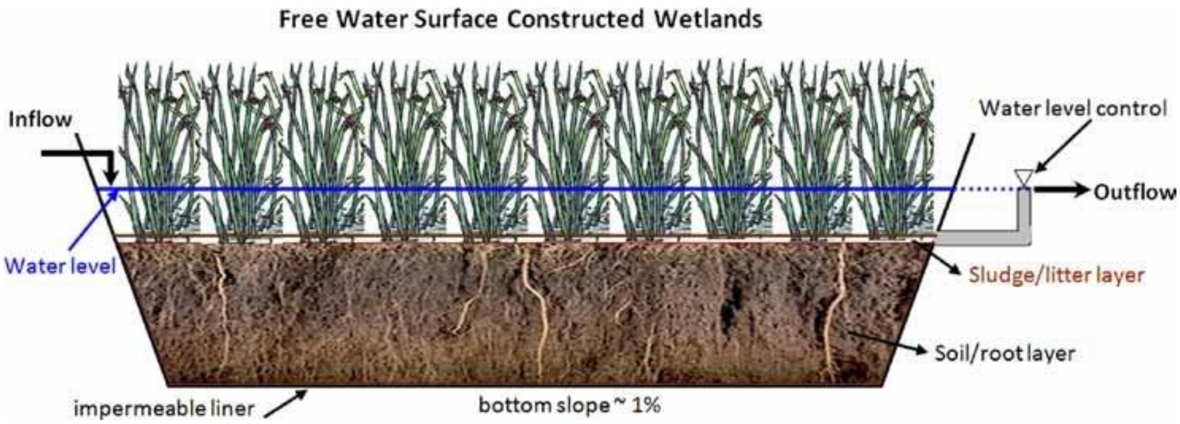

Figure 2: Components free water surface flow constructed wetland [53].

2.5.3.2. Subsurface flow constructed wetlands (SSF CWs)

This is a second type of constructed wetlands which consists of porous media substrate which maintain the all-water level below the surface. They can also flowed on and also prevent the mosquito problems of surface flow CWs [28]. This type of constructed wetland is classified into three categories according the flow direction. There is vertical flow CWs, horizontal flow or vegetated submerged CWs and hybrid constructed wetlands.

Normally, there is a small amount of oxygen in the subsurface flow constructed wetlands however the vertical flow bed CWs are more aerobic and is need small surface area than horizontal ones [50].

2.5.3.2.1. Vertical Flow Constructed Wetlands (VFCWs)

VFCWs are wastewater treatment systems with macrophytes rooted in a gravel or sand bed that is usually of 0.6 to 1 m depth. They differ from horizontal ones in terms of feeding method, water flow direction and filling media [54].

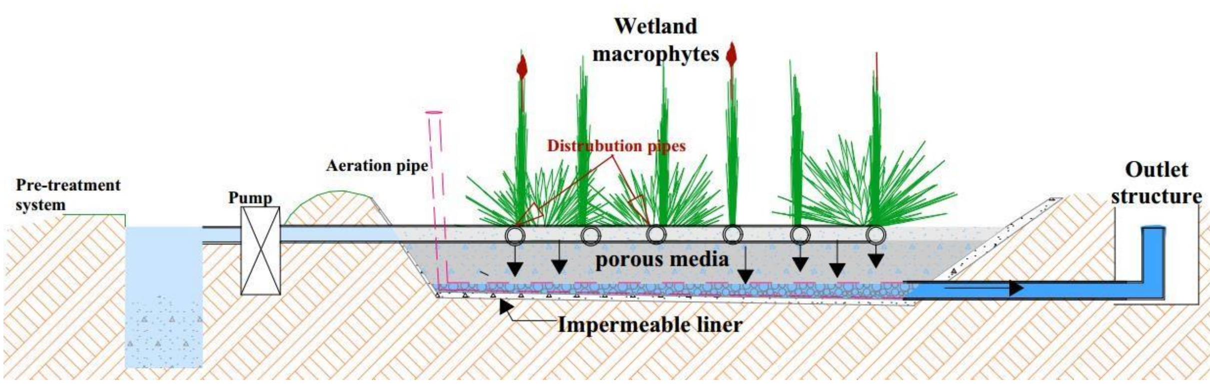

Figure 3:Components of a vertical flow bed constructed wetland [25].

The cross-section of Vertical flow constructed wetland is different to those of Horizontal Flow (HF) wetlands. They are suitable for nitrification because, they possess high amount of oxygen transfer capacity than HF CWs. Oxygen transfer is accomplished through the use of diluted oxygen in wastewater, convection during continuous loading, and diffusion processes that takes place between doses [55].

They require less land per person equivalent with respect to Horizontal subsurface flow constructed wetlands (HSSFCWs). Their disadvantage, they have higher operation and maintenance requirements because wastewater must be pumped continuously on the wetland surface [51]. They are also very effective in ammonia nitrogen removal due to the better aeration capability, but they are poor removal of phosphorous due to insufficient contact time between the wastewater and the substrate [53]

2.5.3.2.2. Horizontal subsurface flow constructed wetlands (HSSF CWs)

This type comprises of different substrates such as gravel or soil beds generally planted with common reeds. Meanwhile water moves horizontally apart the bed below the surface across pores of the substrates such as porous media and the plant roots, there is no water surface displayed to the atmosphere like in SF CWs. As a result, the life issue to ecology and humans is minimized, and mosquito breeding is restricted in this type of CW [56].

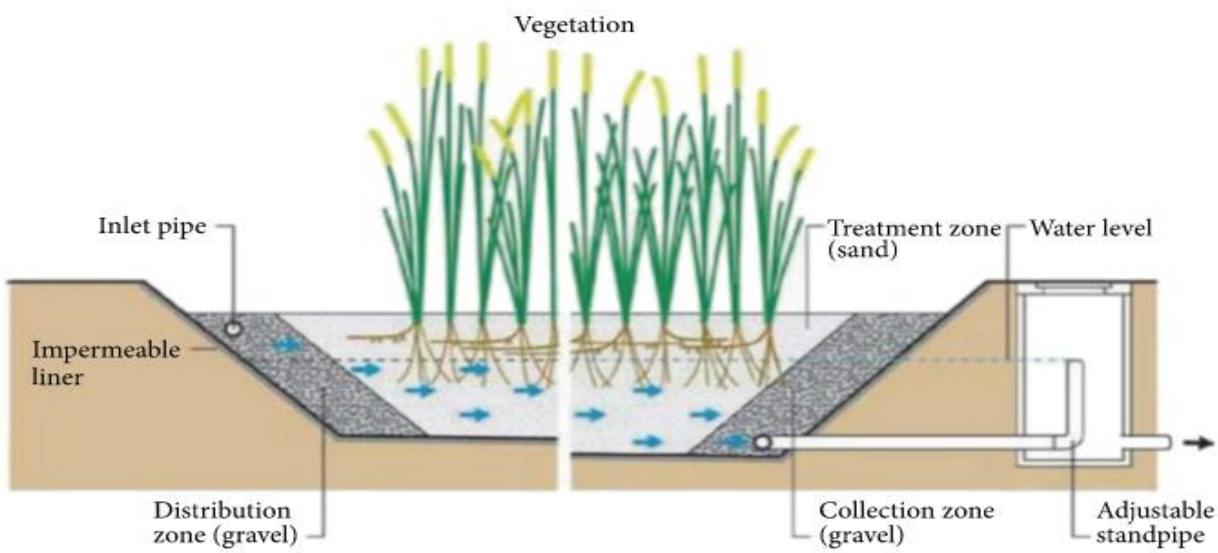

Figure 4 : Components of a horizontal subsurface flow constructed wetland(HSSFCW) [57].

This kind of CW showed to be extremely powerful for the treatment of municipal wastewater also domestic wastewater, removing nutrients (nitrogen, phosphorus) [52]. To improve the performance of HSSF CWs, there are suggestion of various system design modifications, such as return back effluent, wastewater step-feeding, increasing water level and using gravity filters with special substrate to treat effluent [56].

a) Design parameters

i) Preliminary treatment

SFCWs are mainly intended for secondary or tertiary treatment of wastewater followed by a septic tank which is taken a preliminary step. At this step, most of the solids are removed where they are deposited to the bottom and require anoxic bacteria in order to be degraded [43]. Preliminary treatment is required due to the high concentrations of suspended solids which may cause the system to be clogged and reduce its performance [41].

After the pretreatment, the remaining suspended solids are successfully removed by filtration and sedimentation. The accumulation of trapped solids is a significant threat to the performance of horizontal flow systems because the solids can clog the bed. Thus, the successful preliminary treatment is required for HF systems [42,58].

ii) Depth and bottom slope

The wetland beds with slope less than 2.5% should use filtration materials which are coarse while wetland beds with slope less than 1% should use filtration materials which are fine. The wetland having 0.27m of water depth shows high removal efficiencies in a bed of deep between 0.6 to 0.8m. The nitrification and denitrification depend on depth of wetland, if the wetland is shallowed there is sufficient oxygen, this favors nitrification to take place while for wetland which is deeper there is two zones: aerobic and anaerobic which favours both nitrification and denitrification. Considering that almost all aerobic processes take place within 35 mm of the plant roots. If a substrate with suitable flow characteristics is used, a minimal bottom slope is required [43,59].

iii) Filtration media

Substrates such as soil should be used to promote the growth of plant and improve the filtration of wastewater entering the system. But they are inadequate to keep high hydraulic conductivity. Some studies conducted by various authors demonstrated that when coarser gravels are placed at inlet and outlet, this reduced the clogging rate of the system [43,60]. In HSSF CWs, filtration beds are mostly anaerobic. Thus, it is suggested that the effluent concentration of dissolved oxygen is generally less 2 mg/l. But, some systems give high concentration of DO greater than 5 mg/l [61].

iv) Sealing the bed

The sealing of the bed allows constructed wetlands to be placed in areas with relatively high-water tables where drain fields cannot function. It is better to used plastic liners and protect them using sand or geotextile in order to reduce the penetration rate of the roots and damage by sharp edges [58,61]. For system designed to remove nitrogen in wastewater, it is better to use fine grained soil because it has high adsorption rate than coarse grained soil [42].

v) Macrophytes

Plants in constructed wetlands known as macrophytes are an important component of a constructed wetland. They provide a home for animals such as birds and frogs, as well as a local green space.[45]. Plants used in constructed wetlands are classified into three categories where there is floating plant, emergent plant and submerged plant. Systems consist of floating plants can remove nitrogen at high rate through harvesting due to several harvesting plan.

The ability of emergent plants is quite limited, particularly in constructed wetlands for treating municipal or domestic sewage [62].

The plants utilized in constructed wetlands need to be patient to high nitrogen load and plentiful underground organs (roots and rhizomes) in order to give substrate for attached bacteria and generate oxygen of areas close to roots and rhizomes [40]. Nitrogen and phosphorous are taken as the primary nutrients in the life process of wetland plants. As a result, the availability of nitrogen and phosphorous is critical in the development of wetland plants in constructed wetlands [63].

As these nutrients are utilized by the plants in their life cycle i.e., wetland plants reduce the amount of nutrients presented in wastewater. During development period, plants reduce the amount of ammonia and phosphate in municipal wastewater approximately 10-20% [38,54]. The nitrogen removal varies for different plant species due to the oxidation rate of wetland matrix, donation of labile carbon and transpiration. Also, seasonal variations and artificial aeration can cause different responses in different plant species [64].

The aerobic condition for plant is essential for nitrogen removal. Because oxygen flux decreased rapidly after 35 mm from the root, plants with rhizomes spaced further apart will be less efficient in nitrogen removal. Allen showed that all plants improve treatment capacity of SSFCWs with respect to unplanted [65].They provide a suitable environment for microbial development and enhance the transfer of oxygen into the root zone which is part of the filter bed [61].

vi) Treatment efficient

Several factors that can affect the performance of constructed wetlands such as hydraulic properties, temperature, vegetation, wind, shape of the system, inlet–outlet configuration, width-to-length ratio, depth and baffles. The less treatment efficiency can take place when constructed wetlands are designed without taking into account the influence of change of the filter medium on the hydraulic parameters and the hydraulic performance of the system [66].

Different authors investigated the impact of artificial aeration and type of macrophyte on nitrogen removal and storage. The results they obtained showed that the highest removal of nitrogen was achieved in summer period in a planted and aerated systems. Also they showed that denitrification was the main mechanism for nitrogen removal most treatments reached 47–62% of total nitrogen removal, plant uptake reached less than 20% of the removal while sedimentation was controlling in unplanted and non-aerated systems [64].

Oxygen plays a very crucial role in constructed wetlands to remove nitrogen. Nitrification is a process which performs well in hot season because when the temperature is less than 10°C, the efficiency of the treatment system reduced. Denitrification can be restricted in constructed wetlands in absence of carbon and insufficient oxygenation. Normally, denitrification reports for approximately 50% of nitrogen removal in constructed wetlands [62,64].

The performance of horizontal subsurface flow constructed wetlands for nitrogen determined by biological activity which may be altered in winter period because that biological process depends on temperature. Reduction of winter temperatures, shortening of oxygen availability are the restricted factors affecting the nitrogen removal in horizontal subsurface flow constructed wetlands during the growing season [46].

The redox potential, pH value, Fe and Ca are the parameters governing the adsorption and retention of phosphorus in wetlands. Horizontal subsurface flow generally does not remove large amounts of phosphorus from the wastewater due to lack of appropriate conditions favor the removal of phosphorus in these systems. The main removal mechanisms are chemical precipitation and physico-chemical sorption processes because they are free to the temperature [41,61].

Several authors reported that the removal of ammonia, nitrate, and orthophosphate were associated to three factors such as existence of vegetation, medium types, and time period for the test. Additionally, they reported that nitrification was the most mechanism for ammonia removal was while denitrification and plant uptake for nitrate removal in planted systems. Adsorption was found to be the most removal mechanism for orthophosphate in the unsaturated soil bed systems [67].

Hydraulic residence time influences coliforms reduction in constructed wetland. The reduction in coliforms in wastewater is due to bacteria dying naturally as they move through the media [58,68].

2.5.3.3. Hybrid constructed wetlands

Hybrid constructed wetlands comprise of both the horizontal and vertical flow systems and the set-up can either be horizontal flow followed by vertical flow wetland and vice versa thus achieving high treatment efficiency especially with high retention time [69].

They are primarily used to enhance the removal of total nitrogen (TN) because they are appropriate for both nitrification and denitrification. The single-stage CWs is not able to achieve high removal of TN due to their incapability to support both aerobic and anaerobic conditions at the same time.

HSSF CWs can produce favorable denitrification conditions, but they are restricted to nitrify ammonia. On the other hand, VF CWs can successfully remove NH_3-N, but denitrification is rare in these systems. Therefore, several forms of CWs can be united to maximize the strength of each type of individual system [70].

2.5.4. Pollutant's removal mechanisms in constructed wetlands

Constructed wetlands imitate the natural chemical and biological occurring in wetlands in removing nutrients and pathogens from wastewater with the basic mechanisms being sedimentation, chemical precipitation, adsorption, microbial interactions and plants uptake, nitrification and denitrification [67]. Nitrogen is mainly removed by nitrification-denitrification processes. Phosphorus are removed by adsorption and precipitation while pathogens are removed mainly through settling, filtration, and biomass adsorption, and once entrapped within the system, their numbers decreased directly due to predation and natural die-off [71].

(i) Nitrification

Nitrification is a biochemical process in which ammonia is oxidized to nitrate and requires aerobic conditions and is performed in two successive oxidative stages: ammonia to nitrite and nitrite to nitrate. There are different bacteria involved at each stage where they are used by ammonia or nitrite as an energy source and molecular oxygen as an electron acceptor, while carbon dioxide is used as a carbon source. During the oxidation of ammonia, the Nitrosomonas is the most useful bacteria while Nitrobacter is the bacteria used for nitrite oxidation. The following are the chemical equations representing these two processes.

$$NH_4^+ + 1.5O_2 \rightarrow NO_2^- + H_2O + 2H^+ \quad (1)$$

$$NO_2^- + 0.5O_2 \rightarrow NO_3^- \quad (2)$$

Nitrification process necessitates a lot of oxygen.

The pH value is crucial in the nitrification reaction as nitrification rates quickly decline where the pH falls to less than 7. There are different factors which affect the nitrification rate, those factors are: temperature, pH, alkalinity, inorganic carbon source, moisture, microbial population, and concentrations of ammonium–N and dissolved oxygen

(ii) Denitrification

Denitrification is a process which takes place in anaerobic, where nitrate utilized as a final electron acceptor and result in stepwise microbiological reduction of nitrate, nitrite, nitric oxide (NO), nitrous oxide (N_2O) to nitrogen gas (N_2) which escape in the atmosphere. There is involvement of denitrifying bacteria (denitrifiers) which can be divided into two groups: heterotrophs and autotrophs. Heterotrophs are microbes that require organic substrates for development and evolution and obtain energy from organic matter. Contrary to autotrophs which utilize inorganic substances as an energy source and CO_2 as a carbon source. Denitrification, is carried out by heterotrophic microorganism under anaerobic conditions. This process is demonstrated in the following equation

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2 \quad (3)$$

The denitrification rate is controlled by different factors such as nitrate concentration, microbial flora, type and quality of organic carbon source, different plant species residues, anaerobic condition, redox potential, soil humidity, temperature, pH value, component of soil and water level [72]. The pH range preferred for denitrification is 6-8. The rate of denitrification increases when the temperature rises over 15 °C. The denitrifiers' optimal temperature was found to be at 30°C [73].

(iii) Plant uptake

Ammonia and nitrate uptake by macrophytes transforms inorganic nitrogen forms into organic compounds that serve as building blocks for cells and tissues. The ability of rooted plants to utilize settled nutrients describes their higher production than planktonic algae. The rate of nutrient uptake and storage by plants is determined by the nutrient concentration of their tissues. Plant uptake also contributes to nitrogen removal in wetlands since they require nitrogen for growth however, the amount is usually insignificant in comparison to the amount of nitrogen loaded into the wetland by the wastewater [74,75].

(iv) Sedimentation

Sedimentation is one of the main mechanisms to reduce the pathogens. Bacteria are collected on media grains and sediments, the bottom layers of CWs can be taken as the sink of pathogens.
Fecal coliforms are removed highly than other bacteria because they have high settling velocity.

(v) Filtration

Filtration has been identified as the primary removal mechanism of total coliforms and E. coli. A pretreatment stage helps to remove coliforms to some extent. In this step, generally large organic particles are maintained, hence, in the CW bed pathogens is associated with smaller organic particles. Pathogen are filtered in wetland bed because they move with small particles [76].

(vi) Adsorption

This mechanism helps in the removal of pathogens and phosphorus. Adsorption of microorganisms is closely related to filtration due to various interactions between the plant roots, the filter media grains, and the biofilm that surrounds them. The features of the media particles, such as grain size and type of medium affect coliforms adsorption. Phosphorus removal can be achieved in constructed wetlands by adsorption in soil and a small amount is also taken by the plants for growth [45]. There is a need of substituting the filter media because phosphorus removal depends on the sorption capacity of filter substrate [70].

2.5.4.1. Role of macrophytes for nutrient removal in constructed wetlands

The macrophytes play a crucial role in nutrient removal and storage, either directly or indirectly. The immediate process of nutrient isolation involves the absorption of soluble inorganic nitrogen and phosphorus from the water column or settleable materials, uptake and deposit in plant tissue. Connected microbiota, epiphytic microflora, and related biofilm populations require plant surfaces (leaves, stems, and roots) facilitates microbial uptake, conversion and storage of nutrients. Because inorganic nitrogen and phosphorus are essential for plant development, it is better to select plant which have high absorption capacity of inorganic nutrient and transform to organic plant biomass, this can help to maximize the reduction of those nutrients from wastewater effluent. Those plants must have a long growth season, be very effective, and be able to store a lot of nutrients in plant biomass [77].

Floating plants play a role of removing nutrients from the water column, since rooted plants remove nutrients directly from the sediments. When plant uptakes nutrients, they can move from one part of that plant to another. In wastewater treatment systems, plant uptake is an essential nutrient removal process. Nutrient's bioaccumulation is also one of the mechanisms of removing them in the wastewater by constructed wetlands i.e., the direct uptake and deposition of nutrients.

2.5.4.2. Role of macrophytes in pathogens removal in constructed wetlands

Macrophyte plants play a crucial role in the pathogen removal in constructed wetlands. Some plants are thought to produce chemical compounds that can help or hurt bacteria's life. Macrophytes are also known to excrete substances into the rhizosphere that might harm pathogens. These excretions were used in the elimination of total and fecal coliforms in CW because they were thought to be associated to biofilms [78].

2.5.5 History and presentation of constructed wetlands

Pollutant removal in constructed wetlands is accomplished through a variety of physical, chemical, and biological processes. Nitrogen removal is driven by biological microbial processing via nitrification and denitrification. Some greenhouse gases are released during the microbial conversion. The amount of greenhouse gas produced by constructed wetland systems increases as the area covered by them expands. When constructed wetlands are overburdened for an extended period of time, their treatment capacity reduced [45].

Table 2:The following table summarizes the findings of several authors on constructed wetlands.

Constructed wetland type	**HSSFCW**	**HSSFCW**
Media	Gravel	Volcanic tofa
Type of wastewater	Domestic wastewater	Domestic wastewater
Flow rate	17m^3/day	26 L/day
Hydraulic retention time	3 days	5 days
Nitrogen	TN: 7.1%	
N-NH_4^+		63.8%
N-NO_3^-	82%	
Phosphate	38%	
E. coli (logFU/100ml)	0.35	
Reference	[79]	[80]

Table 3: Pollutants removal in HSSFCW[54].

Pollutant	Influent(mg/L)	Effluent (mg/L)	Efficiency (%)
TN	46.6	26.9	43.3
$N\text{-}NH_4^+$	38.9	20.5	48.3
$N\text{-}NO_3^-$	4.4	2.9	34.1
TP	8.75	5.15	41.1

Research conducted for the effectiveness of subsurface flow constructed wetland designed to treat domestic wastewater carried out in Dar es Salaam University in Tanzania in 2012, authors found that the planted constructed wetland had high pollutants removal than unplanted one.

The results obtained during this study were follow: The planted CW showed high removal efficiency of pathogens where E. coli and Fecal coliforms were removed to 92.9% and 93.2% respectively while the removal efficiencies for unplanted CW were 75.2% and 58.7% respectively.
The percentage nitrate/nitrite (combined: NOx) removal were 58.1% for planted and 21.6% for unplanted CW. The phosphate percentage removal was 40.1% for planted and 5.2% for unplanted CW. The temperature values during the study period ranged from 29 to 33^0C [81].

There is also an author who carried out a research in four HSSF systems operating in the northern region of Portugal, their findings showed that an average removal efficiency of $N\text{-}NH_4^+$ varied between 4% and 51% [82]. Although other authors made a study in an HSSF bed situated at Interior Centre of Portugal, the results showed an average removal efficiency of 76.3%, 78.8% and 80% for TN and $N\text{-}NH_4^+$, and $N\text{-}NO_3^-$ respectively [83].

Several authors in their study of performance and temporal variation of a full-scale horizontal constructed wetland for removing nitrogen and phosphorus from domestic wastewater where they were using reed as wetland plant, the obtained findings during those studies showed the mean removal efficiencies of TP were 23%, 27.5% and 12.9% [82].

The above study was carried out at low and high temperatures about 11 and 20^0C. Different authors investigated the effects of three macrophyte species (Phragmites australis, Typha angustifolia, and Phalaris arundinacea) and artificial aeration on the variation of greenhouse gas production (Nitrous oxide) over three different period using an experimental constructed wetland [64].

Total nitrogen (TN) removal was found to be higher in the summer and in planted with aerated units, with Typha angustifolia-planted systems. The removal of oxidized nitrogen was greatest in planted and aerated systems. Also, results showed that denitrification was the primary nitrogen deposit in most treatments showed 47–62% of TN removal, while in sedimentation was controlling in unplanted non-aerated systems. Nutrients uptaken by plants were very low approximately 20%. In few words greenhouse gases were generated highly in unplanted and non-aerated system during the dry seasons. Different authors concluded that the removal efficiency of $N\text{-}NH_4^+$ was very high in aerated wetland than the non-aerated wetland reactors because aeration favours nitrification [63].

2.5.6. Comparison of subsurface constructed wetlands and ponds

The following are the main reasons why subsurface flow CWs should be preferred over ponds:

In Subsurface flow CWs water flow belowground, thus, mosquito breeding is not promoted.

Subsurface flow CWs produce clear water, while ponds have a lot of algae production which affect the effluent quality. It is not easy to build ponds in neighbourhood because of they produce unpleasant odour and promote mosquitos.

No sludge generated in CWs except in pre-treatment stage while in pond there is sludge accumulation which may cause the system to be clogged. Ponds have advantages over subsurface flow CWs in that they are easier to design and build, do not require a substrate (sand), and have lower capital costs for large-scale plants [45].

2.6. Management of natural wastewater treatment systems

Management is a set of all activities and tasks undertaken for achieving goals by continuous activities. The poor management systems of constructed wetlands or other natural wastewater treatment cause the reduction in the performance of the treatment system, this led the system to release the effluent which not comply the standards and pollute the environment. To avoid those stated above issues, various tasks should be undertaken in order to manage the treatment system in a sustainable manner.

2.6.1. Construction considerations

The construction of CW, like any other engineering facility, follows a standard and structured approach that includes the use of local craftsmen or contractors. Normally, they are provided with drawings and specifications, as well as assurances that the work meets engineering quality objectives and is accomplished within schedule and budgetary constraints, all under the designer's supervision.

Most contractors and local builders, on the other hand, are unaware of and unprepared to understand the technology and its main functional components. They look at the CW system from a structural standpoint rather than a functional standpoint. Contractors and builders commonly make mistakes including providing inappropriate inlet and output pipe levels to satisfy required hydraulic requirements, providing the wrong size of substrates, and introducing soils into the system to facilitate the growth of wetland plants [84].

2.6.2. Operation, maintenance and monitoring

Cw needs regular monitoring and maintenance to be sure that it may work properly for a long period. The operation and maintenance include the requirements for safety, water control, desludging, maintenance of systems, embankments and vegetation, control measures for vectors and pests and materials with harmful pollutants during maintenance operation. Monitoring and maintenance are required to comply standards for effluent wastewater [85].

The operation problems occurred are seepage through the leakage, fluctuation of flows and inadequate performance monitoring of the CW systems. Thus, the need for users' training operation, maintenance and monitoring of CW during decommissioning phase.

The well managed CW create pleasing environment for recreational purposes and enhance biodiversity value due to attraction of birds, reptiles etc.

2.6.3. Social mobilization and awareness rising

Social mobilization is a concept that entails the creation of social networks for initiatives in development projects. The contribution of people in any development program is the prerequisite for keeping any accomplishment. Social mobilization does not limited only people in the community, it can reach in all sector levels as well as services delivery agencies. So, for a CW technology to successful, it is critical to implement social mobilization in the concerned area.

2.6.4. Costs consideration for CW

The cost for putting up a facility in place as well as the operation and maintenance costs should be considered.

(i) Capital cost

The value of land uses should be considered. The buffer area is recommended between wetland cell (5m wide). Construction costs this deals with all materials will be required. There are also labor and media costs to consider. Planting cost depends mainly on planting density and the plant species used. To avoid damage to existing habitats and the unintentional introduction of exotic species, transplanting advice typically recommends sourcing from accredited nurseries.

(ii) Maintenance and monitoring cost

Maintenance: Due to a lack of regulatory requirements and financial incentives, maintenance activities usually do not considered for the CWs studies and knowledge and comprehension of the required maintenance.

Monitoring: Majority of the CWs are completely unmonitored after construction, which lead to less effective and in the lack of corrective actions. Due to lack of regulatory and apply in the field, the cost of monitoring which could be produced by farmers or local authorities is currently unknown and could be significant if the polluter pays principles are putted into action and farmers are required to communicate this issue. However, sampling and analysis of waster is needed to ensure that the effluents comply the standards.

2.6.5. Benefits aspects of CW

Quite often CW technology is not easily up taken up because users are not well informed about the advantages of using it.

CWs work for many functions that produce goods and services to society. Their benefits are the following: hydrology/water quality, landscape improvement, fauna habitat, recreational and educational activities. The function CW associated to water quality includes supply of treated water appropriate to be reused in different activities.

2.6.6. Financial mechanisms

Cw technology has not been well up taken because stakeholders are not properly educated about different financial mechanisms for the technology. Financial mechanisms, mean source of money for both capital investment and operation and maintenance costs. The financial mechanisms should be applied at different levels. These levels can be National level, Local level, communities and civil societies level and household level. All those level should be well informed about the financial mechanisms and the role of each level in funding [49, 84-86].

Chapter 3: MATERIALS AND METHODS

3.1. Description of project areas

The Nyarutarama natural wastewater treatment system was located in Kigali City-Rwanda, Gasabo District, Remera Sector and Nyarutarama cell. This system received settled sewage from Juru estate and Green Hills Academy school. It treated wastewater from septic tanks. Nyarutarama hybrid pond consisted with three ponds: The first pond which is the largest one had dimensions of 101 m of length, 66 m of width and 1.5 m of depth. It had two zones which was aerobic and anaerobic. The second pond known as Water-lettuce covered pond because it was planted with water hyacinth and was smaller than the primary pond as shown with its dimensions which were 73 m of length, 42 m of width and 1.2 m of depth. The third pond considered as a constructed wetland, was the smallest one among the two first ones as shown by its dimensions which were 67 m of length, 43 m of width and 0.9 m of depth [87].

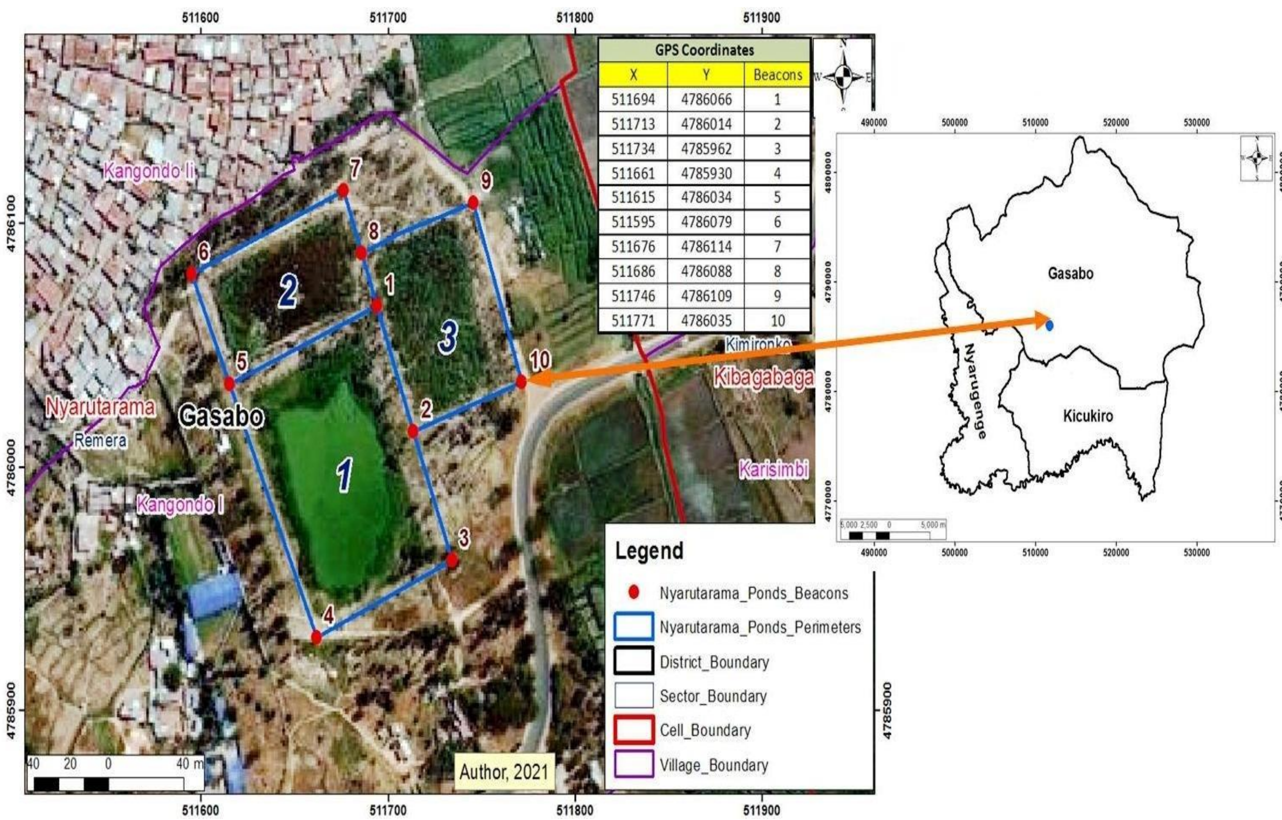

Figure 5: Map of Kigali showing the location of Nyarutarama hybrid pond.

3.2. Sampling

The sampling points were located at inlet and outlet of the primary pond, at the outlet of the second pond (water lettuce- covered pond), the last sampling point was located at the outlet the third pond known as constructed wetland.

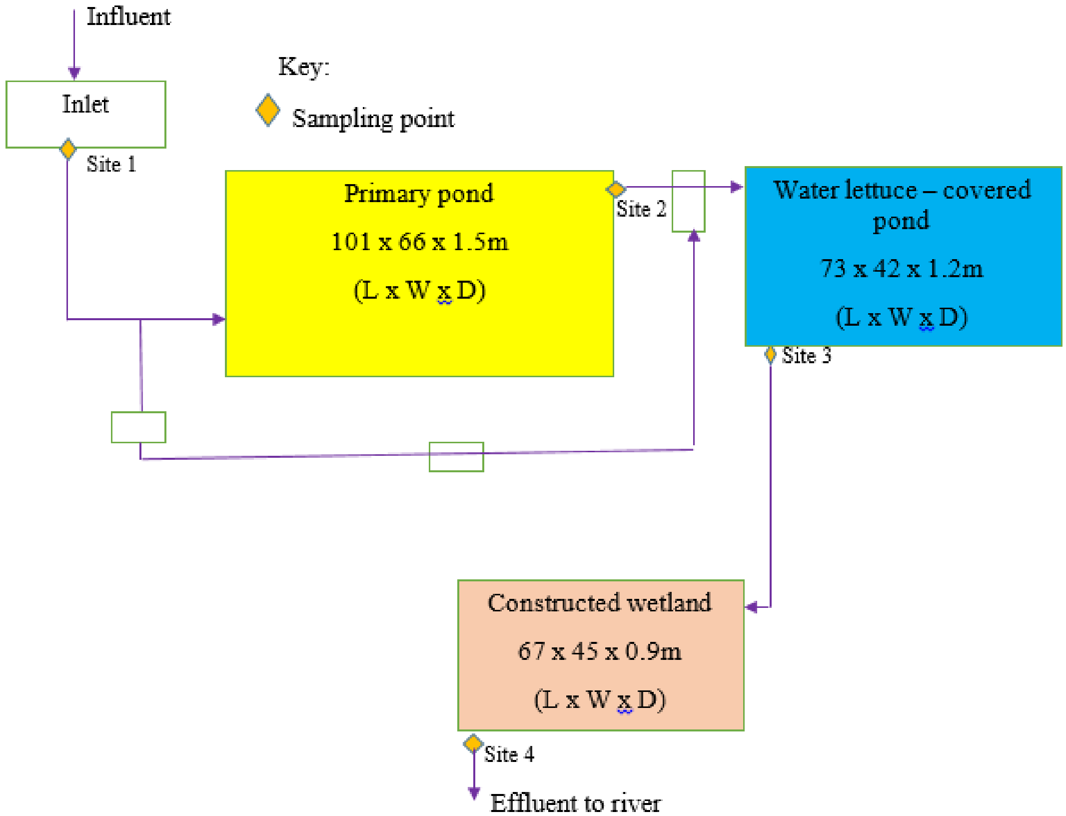

Figure 6: Design of the Nyarutarama Ponds showing sampling points.

Samples were collected for both inlet and outlet of the system for period of six weeks where samples were taken once a week from September to October, 2021.

3.2.1. Sample techniques

The grab samples from the four sampling points (influent and effluent of primary pond, outlet of secondary pond and outlet of third pond known as CW) at Nyarutarama ponds and were collected in 500 ml plastic bottles and sterilized bottles for microbiological samples analysis and putted suitable cooler boxes, where they were transported and preserved carefully in CST Chemistry laboratory and stored at 4°C for further analysis.

3.2.2. Methods for water sample collection

The following parameters are used to control the performance of the system: The physical parameters such as pH, Temperature, Electrical conductivity (EC), Dissolved oxygen (DO), chemical parameters: Ammonium-nitrogen (NH_4-N), Nitrite-nitrogen (NO_2^--N), Nitrate-nitrogen (NO_3^--N), Total nitrogen (TN), Orthophosphate (PO_4^{3-}-P), Total phosphorus (TP), and biological parameters such as Total coliform, Fecal coliform and Escherichia Coli.

The characteristic parameters were measured according to Standard Methods for examination of water and wastewater 23rd edition [88]. The samples were collected and placed into cleaned plastic bottles and sterilized bottles for microbiological samples analysis and stored in a cooler box contains ice in order to be transported to the laboratory. These have been used to avoid any change which could appear from sample collection to laboratory analysis. A small amount of wastewater was filtered using the appropriate filters at the same day of sample collection.

The laboratory analyses were conducted for filtered and unfiltered wastewater according to the requirements of analytical procedure. Some parameters were analyzed directly upon arrival in the laboratory such as NH_4-N and coliforms. The samples to be analyzed for the next days were stored in the fridge at 4ºC, before analyzing those cooled sample, they were removed in fridge and exposed at room temperatures up to they reached the room temperature.

3.3. Analysis methods and materials

The methods and instruments which were used to analyze nutrients, pathogens and some physical parameters were summarized in the table 4

Table 4: The methods used to measure the water quality parameters for the ponds and wetland samples

Parameter	**Analytical method**	**Analytical instrument used**
Temperature		HACH field testing kits.
pH	Electrometric method	HACH field testing kits
Electrical conductivity (EC)		Conductivity meter
DO	Membrane electrode method	HACH field testing kits
NH_4^+- N		UV-Vis spectrophotometer λ= 690nm
NO_2^-N	4500-NO2 B. Colorimetric Method	UV-Vis spectrophotometer λ= 543 nm
NO_3^-N	4500-NO_3^-E. Cadmium Reduction Method	UV-Vis spectrophotometer λ= 543 nm
TN	4500-N C. Persulfate Method	UV-Vis spectrophotometer λ= 543 nm
PO_4^{3-}P	4500-P E. Ascorbic Acid Method	UV-Vis spectrophotometer λ= 880 nm
TP	Persulfate Digestion Method	UV-Vis spectrophotometer λ= 880 nm
Total coliform	9221 B, E, F	
Fecal coliform		
E. Coli		

The physical parameters such as temperature, pH, dissolved oxygen, and electrical conductivity were measured in situ using HACH field testing kits. EC records was standardized at 25ºC. HACH field testing kits were calibrated in the laboratory before each sampling to improve reliable measurements.

3.4. Determination of pollutants removal efficiencies

Removal efficiencies (RE) of pollutants from natural wastewater treatment system were calculated as shown in the equation 4

Removal efficiency (%) = $\frac{Ci-Ce}{Ci}\ x\ 100$ (4)

Where: Ci = Influent concentration, Ce = Effluent concentration

3.5. Survey about sustainable management of natural treatment systems

In order to get information concerning the management of Nyarutarama hybrid pond, questionnaires were elaborated. The survey was conducted as a kind of key informant interviews. This was done by interviewing local authorities (village, cell and sector level), different experts in natural wastewater treatment systems, those in charge of hygiene and sanitation in different level, one expert in WASAC was also interviewed, some beneficiaries of Juru estate who generated sewage which were treated in Nyarutarama natural hybrid pond how they were ready for paying maintenance funds for treatment systems and few people who lived near that system.

Chapter 4: RESULTS AND DISCUSSION

This section presented the findings in the analysis of various parameters such as nutrients and pathogens at Nyarutarama hybrid natural pond by comparing the efficiency removal of three ponds of Nyarutarama and the results from key informant interview and their discussion with what other authors have been done on the natural treatment system for municipal wastewater and with the national and international standards for effluents of municipal wastewater also the successful methods for sustainable management of natural wastewater treatment systems. Some of the results are presented in the appendices.

The loading rate of Nyarutarama hybrid natural pond was about 355m^3/day in 2007, during this study the loading rate was 357 m^3/day, means even if the citizens in Juru estate has increased, the flow rate did not much change.

4.1. Nutrients and pathogens removal efficiencies

4.1.1. Ammonium-nitrogen

The following table shows the sampling date, concentrations of ammonium-nitrogen (NH_4-N) and the efficiency removal for the primary facultative pond, water lettuce- covered pond and constructed wetland of Nyarutarama hybrid natural pond.

Table 5: Concentrations of ammonium-nitrogen and their removal efficiencies in Nyarutarama hybrid pond

Sampling date	**Primary facultative pond**			**Water lettuce-covered pond**			**Constructed wetland**		
	Influent Conc. of NH_4-N (mg/L)	Effluent conc. of NH_4-N (mg/L)	Removal efficiency (%)	Influent Conc. of NH_4-N (mg/L)	Effluent conc. of NH_4-N (mg/L)	Removal efficiency (%)	Influent Conc. of NH_4-N (mg/L)	Effluent conc. of NH_4-N (mg/L)	Removal efficiency (%)
Week 1	0.723	0.628	13	0.628	0.489	22	0.489	0.218	55
Week 2	0.676	0.612	9	0.612	0.527	14	0.527	0.292	45
Week 3	0.718	0.631	12	0.631	0.532	16	0.532	0.235	56
Week 4	0.637	0.552	13	0.552	0.431	22	0.431	0.176	59
Week 5	0.792	0.612	23	0.612	0.429	30	0.429	0.185	57
Week 6	0.814	0.703	14	0.703	0.573	18	0.573	0.275	52

The table 5 showed the concentration of ammonium-nitrogen is slightly decreased in primary facultative pond and moderately in water lettuce-covered pond considered as maturation pond because of its deep of 1.2 m and highly decreased in constructed wetland as presented in the figure 7. The average removal efficiency for primary facultative pond, water lettuce- covered pond and constructed wetland were 14%, 20% and 54% respectively. The results showed that the highest percent reduction of NH_4-N was obtained from constructed wetland and the lowest was from primary pond. This indicated that the constructed wetland was the best system in removing NH_4-N in municipal wastewater.

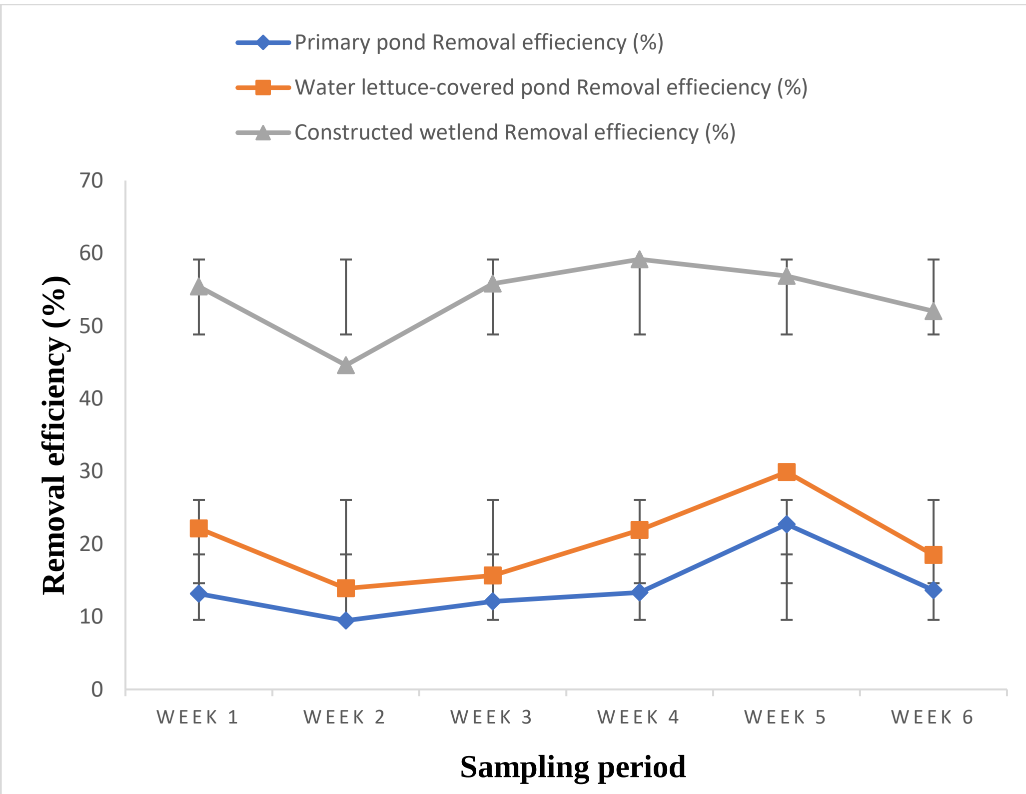

Figure 7: Comparison of removal efficiencies of ammonium-nitrogen of primary and secondary ponds and constructed wetland.

The NH_4-N is a preferred form of nitrogen uptake by plants, was plentiful in the plants, indicating that ammonium was high in the plants, that is the reason why, it was removed very little in primary facultative pond which was unplanted one, the removal efficiency started to increase in the water lettuce- covered pond and became highly removed in constructed wetland due to its macrophyte which uptaken the NH_4-N . Nitrification was also the main factor which caused the high removal of NH_4-N at Nyarutarama constructed wetland when they were oxidized into NO_2^--N where further process continued.

The highest NH_4-N removal could be related to an increase in water temperature in constructed wetland that enhanced high nitrification rate [89]. Nevertheless, the average removal of NH_4-N in constructed wetland obtained in this research was less than the NH_4-N removal efficiency published in Palestine which was 92% [58]. But was higher than that reported in Egypt(45%)[90]. And the obtained RE in this study was approximately to that reported in Ethiopia (65%) [91].

4.1.2. Nitrite-nitrogen

The following table shows the sampling date, concentrations of nitrite-nitrogen (NO_2^--N) and the removal efficiency for the primary facultative pond, water lettuce- covered pond and constructed wetland of Nyarutarama hybrid natural pond.

Table 6: Concentrations of nitrite-nitrogen and their removal efficiencies in Nyarutarama hybrid pond

Sampling date	Primary facultative pond			Water lettuce-covered pond			Constructed wetland		
	Influent Conc. Of NO_2-N (mg/L)	Effluent conc. Of NO_2-N (mg/L)	Removal efficiency (%)	Influent Conc. Of NO_2-N (mg/L)	Effluent conc. Of NO_2-N (mg/L)	Removal efficiency (%)	Influent Conc. Of NO_2-N (mg/L)	Effluent conc. Of NO_2-N (mg/L)	Removal efficiency (%)
Week 1	0.292	0.2	32	0.2	0.128	36	0.128	0.079	38
Week 2	0.245	0.16	35	0.16	0.098	39	0.098	0.056	43
Week 3	0.223	0.161	28	0.161	0.101	37	0.101	0.054	47
Week 4	0.233	0.183	21	0.183	0.125	32	0.125	0.074	41
Week 5	0.205	0.151	26	0.151	0.089	41	0.089	0.048	46
Week 6	0.173	0.125	28	0.125	0.071	43	0.071	0.031	56

The table 6 showed the influent and effluent concentration of NO_2-N in Nyarutarama hybrid pond where there was a comparison of primary facultative pond, water lettuce- covered pond and constructed wetland for six sampling times, it demonstrated that the removal efficiency of NO_2-N was very little in pond systems and started to be high in constructed wetland. The average removal efficiencies were 28%, 38% and 45% for primary facultative pond, water lettuce- covered pond and constructed wetland respectively. The analyzed results demonstrated the variation in the efficiency removal through the three systems of Nyarutarama natural hybrid pond where the constructed wetland was the best to removal NO_2-N in wastewater. The average effluent concentration of nitrite in this study was 0.230mg/L which was less than the effluent standard for domestic wastewater in Rwanda [26].

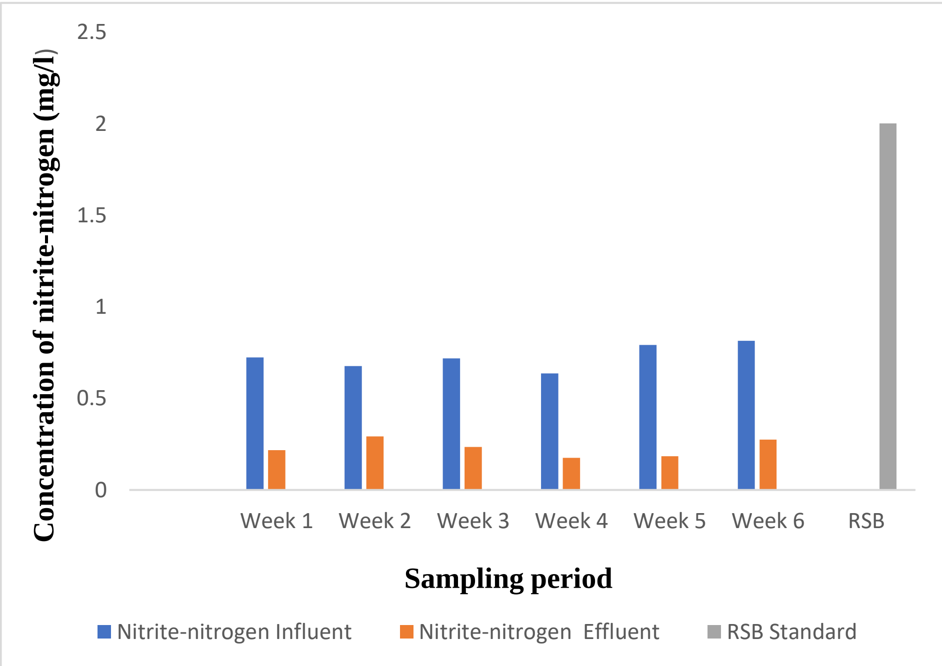

Figure 8: Nitrite-Nitrogen measurement

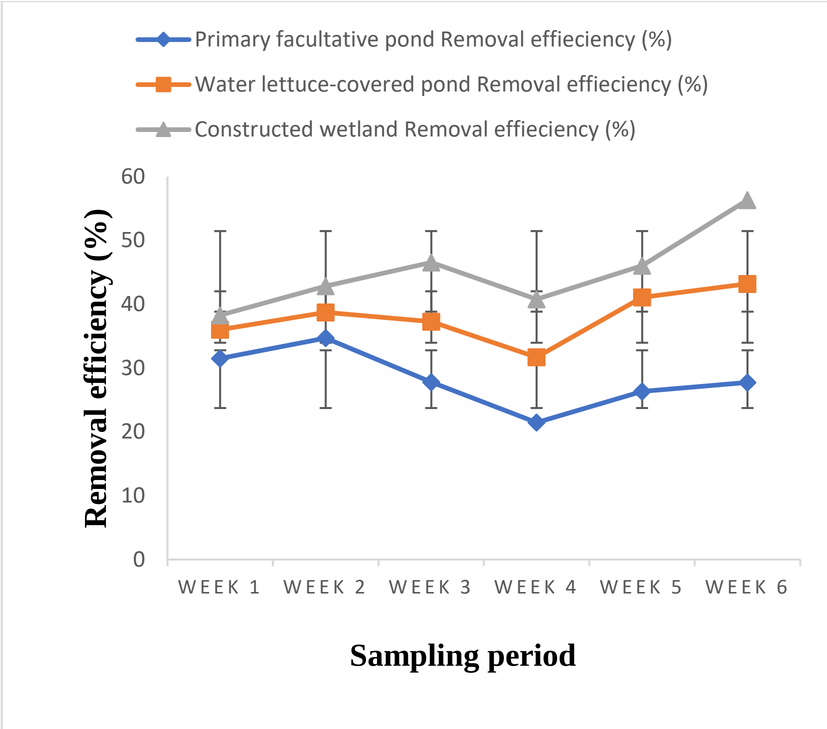

Figure 9: Comparison of removal efficiencies of nitrite-nitrogen of two primary and secondary ponds and constructed wetland

The results in this study showed the lowest and highest removal efficiency were 28% and 45% for primary pond and constructed wetland. The average RE for the whole treatment system was 75% which was lower than that reported in 2013 by another author which was 78% at the Nyarutarama natural hybrid pond [87]. The reduction in performance could be caused by its incomplete nitrification and weak plant uptake due to the oldness of those macrophytes.

4.1.3. Nitrate - nitrogen

The following table shows the sampling date, concentrations of nitrate-nitrogen (NO_3-N) and the removal efficiency for the primary facultative pond, water lettuce- covered pond and constructed wetland of Nyarutarama hybrid natural pond.

Table 7: Concentrations of nitrate-nitrogen and their removal efficiencies in Nyarutarama hybrid pond

Sampling date	**Primary facultative pond**			**Water lettuce-covered pond**			**Constructed wetland**		
	Influent Conc. of NO_3-N (mg/L)	Effluent conc. of NO_3-N (mg/L)	Removal efficiency (%)	Influent Conc. of NO_3-N (mg/L)	Effluent conc. of NO_3-N (mg/L)	Removal efficiency (%)	Influent Conc. Of NO_3-N (mg/L)	Effluent conc. Of NO_3-N (mg/L)	Removal efficiency (%)
Week 1	0.267	0.187	30	0.187	0.108	42	0.108	0.056	48
Week 2	0.308	0.226	27	0.226	0.137	39	0.137	0.07	49
Week 3	0.236	0.166	30	0.166	0.112	33	0.112	0.061	46
Week 4	0.304	0.218	28	0.218	0.126	42	0.126	0.058	54
Week 5	0.33	0.281	15	0.281	0.204	27	0.204	0.119	42
Week 6	0.306	0.215	30	0.215	0.126	41	0.126	0.067	47

The positive removal efficiencies of NO_3-N were attained in all parts of the Nyarutarama natural hybrid pond, showing a decrease of NO_3-N concentration in the effluent as indicated in table 7. The average removal efficiency for six sampling times were 27%, 38% and 48% for primary facultative pond, water lettuce- covered pond and constructed wetland respectively.

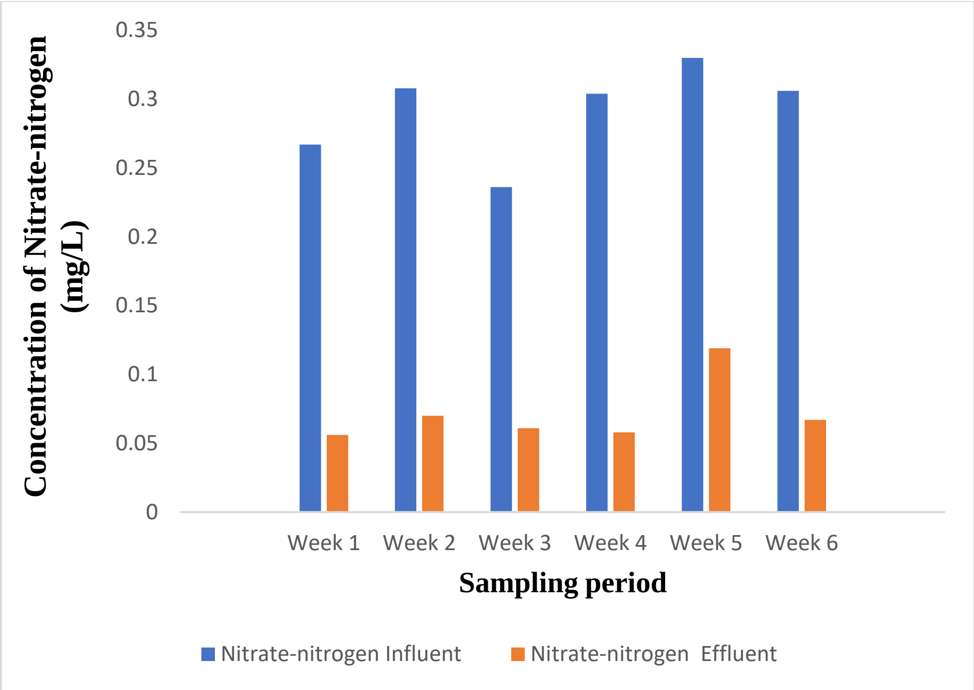

Figure 10: Nitrate-nitrogen Measurement

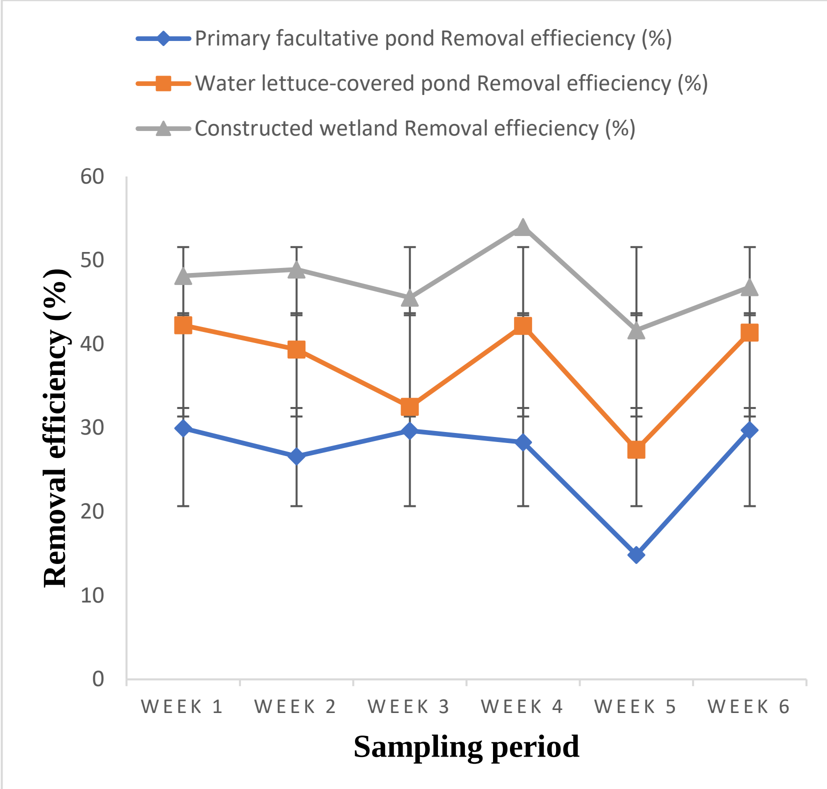

Figure 11: Comparison of removal efficiencies of Nitrate-nitrogen for two primary and secondary ponds and constructed wetland.

The fig. 11 showed the increase and decrease of removal efficiencies of nitrate in Nyarutarama natural hybrid pond, the decreasing of RE was due to the increasing to dissolved oxygen in the system where the nitrification was favored and lead to high concentration of nitrate- nitrogen, and rising of RE is due to the decreasing of DO in the pond or constructed wetland. Primary facultative pond had two sections: anaerobic and aerobic where both nitrification and denitrification occurred and the performance removal of NO_3-N was slightly low. Water lettuce- covered pond favor nitrification because of its short depth, this caused the NO_3-N concentration to rise and plant uptake remained the crucial mechanism to removal nitrate. In constructed wetland, the elimination of NO_3-N was due to denitrification and macrophytes which adsorbed them through their roots [92].

Nitrate concentrations can only be reduced through a process called denitrification, whereby nitrate is converted to dinitrogen. This process occurs only under anaerobic conditions [93]. The overall average effluent concentration of NO_3-N was 0.072mg/L. This value met the discharge standard value set by Rwanda standard board. The discharge standard for nitrate was less than 20 mg/L [26].

The lowest and the highest removal efficiency obtained in this study were 27% and 48% for primary pond and constructed wetland respectively. The RE value of Nyarutarama constructed wetland for NO_3-N was lower than the RE reported Ethiopia which was 68.7% [91]. This was caused by high dissolved oxygen in the CW system. The Overall RE of the Nyarutarama hybrid pond was 75.4% which was lower than the RE report on this system in 2013, which was 85%. The reduction in performance of the system to remove NO_3-N was due to unharvested mature and old macrophytes and return in the system, after decompose into organic matter, the decomposition of organic matter decreased bacteria which could involve in denitrification process.

4.1.4. Total nitrogen

The following table shows the sampling date, concentrations of total nitrogen (TN) and the removal efficiency for the primary facultative pond, water lettuce- covered pond and constructed wetland of Nyarutarama hybrid natural pond.

Table 8: Concentrations of total nitrogen and their removal efficiencies in Nyarutarama hybrid pond

Sampling date	Primary facultative pond			Water lettuce-covered pond			Constructed wetland		
	Influent Conc. of TN (mg/L)	Effluent conc. of TN (mg/L)	Removal efficiency (%)	Influent Conc. of TN (mg/L)	Effluent conc. of TN (mg/L)	Removal efficiency (%)	Influent Conc. of TN (mg/L)	Effluent conc. of TN (mg/L)	Removal efficiency (%)
Week 1	1.389	1.209	13	1.209	0.986	18	0.986	0.742	25
Week 2	1.339	1.156	14	1.156	0.891	23	0.891	0.613	31
Week 3	1.377	1.198	13	1.198	1.002	16	1.002	0.735	27
Week 4	1.272	1.12	12	1.12	0.917	18	0.917	0.648	29
Week 5	1.526	1.287	16	1.287	1.014	21	1.014	0.766	24
Week 6	1.929	1.649	15	1.649	1.322	20	1.322	0.985	25

Nitrogen is the extreme pollutant to be taken under consideration in wastewater treatment but removed in pond and constructed wetland at low percentage. The table 8 showed the decrease of TN concentrations and their removal in Nyarutarama hybrid pond. The findings indicated that the average removal efficiency of TN in primary facultative pond, water- lettuce covered pond and constructed wetland were 14%, 19% and 27% respectively. The analyzed samples indicated that the high amount of Total nitrogen was composed by NH_4-N i.e., the municipal wastewater treated in Nyarutarama natural hybrid pond was acidic one.

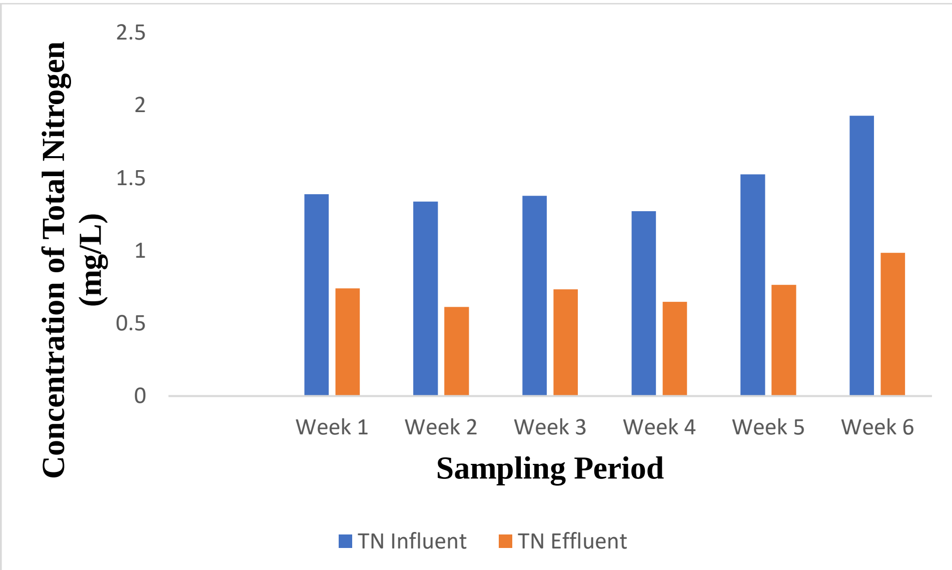

Figure 12: TN measurement

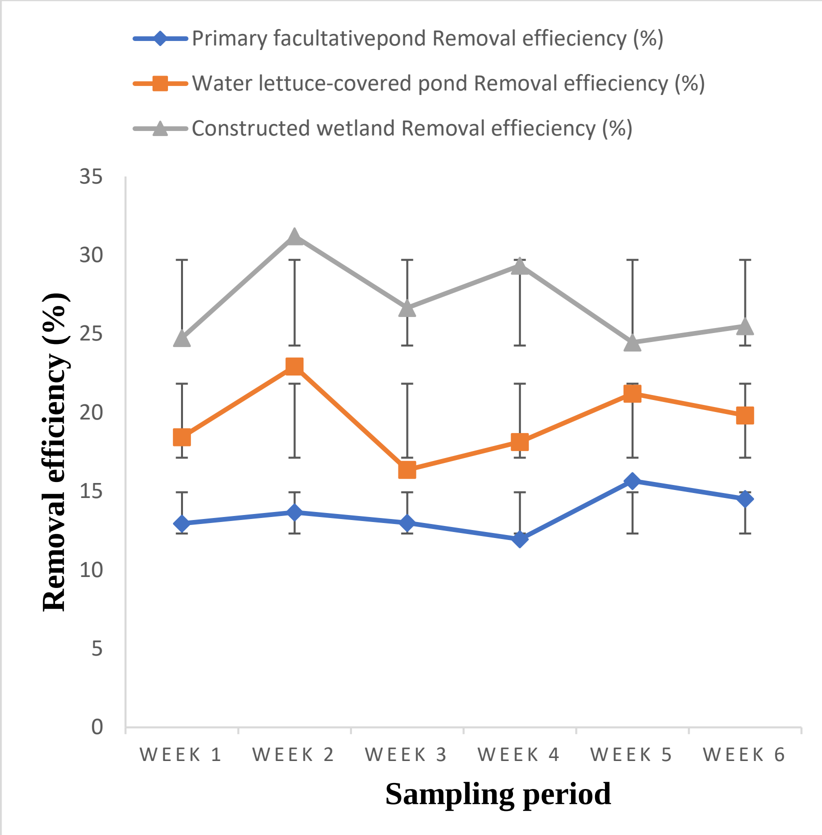

Figure 13: Comparison of removal efficiencies of Total nitrogen of two primary and secondary ponds and constructed wetland.

Ammonification and nitrification processes are the basics mechanisms for nitrogen removal in ponds and CWs. Ammonification transforms the influent organic nitrogen in ammonia and nitrification oxidizes ammonium into nitrogen oxidized forms (NOx-N), where further process continued. Both processes are favored at the range of temperature of 25 to 35^{o}C, in addition for nitrification, concentration of DO about 3 to 4 mg/L and pH around 7.5 are also the factors which favor nitrification [56]. From the tables in appendix of in situ physical-chemical parameters showed that the average temperature and DO concentration in primary facultative pond, water lettuce- covered pond and constructed wetland were 24.3, 23.4 and 25.6^{0}C, 2.5, 3.2 and 5.5 mg/L respectively. But the average pH for those three systems (two ponds and CW) were under 7.5.

The obtained results showed that the water lettuce- covered pond and constructed wetland fulfilled one of the factors which favor nitrification, CW met the conditions for ammonification but the water lettuce – covered pond did not. These explained on the fig. 13 why the removal efficiencies of TN in CW were high than in the water lettuce- covered pond and primary facultative pond.

The average effluent concentration of TN in the Nyarutarama natural hybrid pond was 0.748 mg/L which was also the effluent value of CW, this value met the effluent quality of wastewater set by Rwanda standard board. The discharge standard value was less than 30 mg/L [26]. The lowest and highest RE were 14% and 27% for primary pond and constructed wetland respectively. The overall average RE was 49%. Compared to the similar study in other countries, the obtained results indicated the lower average removal efficiency for CW than the removal efficiency reported in Ethiopia which was 54% [91]. whereas, the result was higher than the removal efficiency reported in Kenya which was 8% [94]. The results showed that the use of hybrid pond i.e., combination of ponds and CWs were more efficiency in removing pollutants.

4.1.5. Ortho-phosphate

The following table shows the sampling date, concentrations of ortho-phosphate ($PO4^{3-}$- P) and the removal efficiency for the primary facultative pond, water lettuce- covered pond and constructed wetland of Nyarutarama hybrid natural pond.

Table 9: Concentrations of ortho-phosphate and their removal efficiencies in Nyarutarama hybrid pond

Sampling date	Primary facultative pond			Water lettuce-covered pond			Constructed wetland		
	Influent Conc. of $PO4^{3-}$- P (mg/L)	Effluent conc. of $PO4^{3-}$- P (mg/L)	Removal efficiency (%)	Influent Conc. of $PO4^{3-}$- P (mg/L)	Effluent conc. of $PO4^{3-}$- P (mg/L)	Removal efficiency (%)	Influent Conc. of $PO4^{3-}$- P (mg/L)	Effluent conc. of $PO4^{3-}$- P (mg/L)	Removal efficiency (%)
Week 1	4.313	2.964	31	2.964	1.624	45	1.524	0.699	54
Week 2	4.146	2.58	38	2.58	1.332	48	1.332	0.518	61
Week 3	5.828	3.561	39	3.561	1.954	45	1.954	0.809	59
Week 4	5.195	3.017	42	3.017	1.574	48	1.574	0.645	59
Week 5	5.523	3.295	40	3.295	1.91	42	1.91	0.884	54
Week 6	5.553	3.351	40	3.351	1.782	47	1.782	0.791	56

The table 9 showed the reduction in concentration of and how they were removed in three systems of Nyarutarama natural hybrid pond. The removal efficiencies for primary facultative pond, water lettuce- covered pond and constructed wetland were 38%, 46% and 57% respectively. These results showed the best performance of CW for removing ortho-phosphate than facultative and maturation pond.

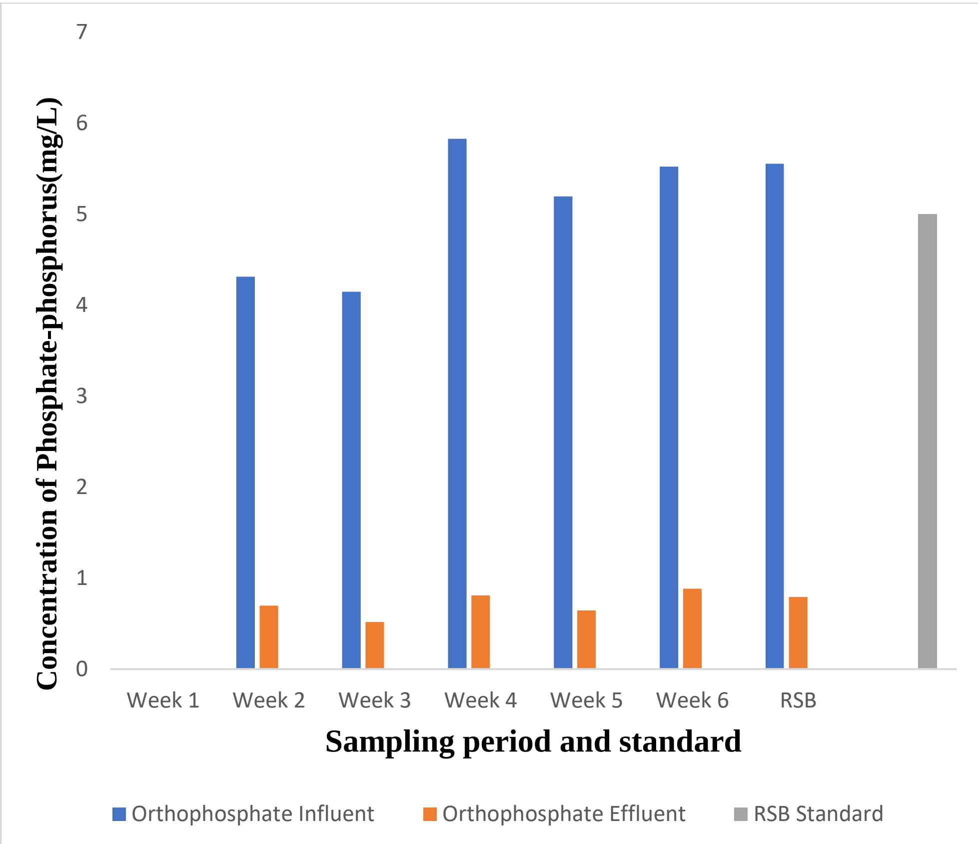

Figure 14: Phosphate-phosphorus measurement

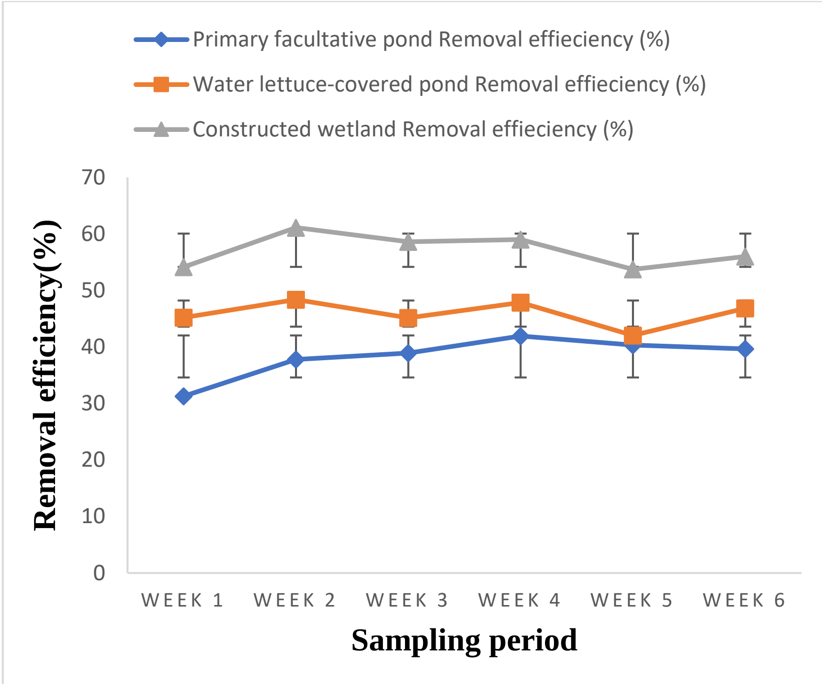

Figure 15: Comparison of removal efficiencies of orthophosphate of two primary and secondary ponds and constructed wetland.

Presence of plants successfully removes PO_4^{3-} because it is easily absorbed by plants. It has been proposed that vegetation, fauna and microorganisms are predominant sink for phosphorous in the short term but substrate is the primary sink for Phosphorous in the long term. In longer term, the phosphorous removal will be declined in the planted systems due to the saturation of Phosphorous adsorption in the substrate. Adsorption is taken as the prime mechanism for phosphorus removal [95].

The average effluent concentration was 0.724mg/L. The obtained result complied the discharge standard which was 5mg/L set by Rwanda standard board [26]. The lowest and the highest removal efficiencies were 38% and 57% for primary pond and constructed wetland. According to other results from the similar work, the result for CW of this study was higher than the removal efficiency reported in Egypt which was 44% [90], whereas was lower than the efficiency reported in Tunisia which was 82% [79].

4.1.6. Total phosphorus

The following table shows the sampling date, concentrations of Total phosphate (TP) and the removal efficiency for the primary facultative pond, water lettuce- covered pond and constructed wetland of Nyarutarama hybrid natural pond.

Table 10: Concentrations of Total phosphate and their removal efficiencies in Nyarutarama hybrid pond

Sampling date	**Primary facultative pond**			**Water lettuce-covered pond**			**Constructed wetland**		
	Influent Conc. of TP (mg/L)	Effluent conc. of TP (mg/L)	Removal efficiency (%)	Influent Conc. of TP (mg/L)	Effluent conc. of TP (mg/L)	Removal efficiency (%)	Influent Conc. of TP (mg/L)	Effluent conc. of TP (mg/L)	Removal efficiency (%)
Week 1	6.257	3.79	39	3.79	2.157	43	2.157	0.995	54
Week 2	5.459	3.368	38	3.368	1.793	47	1.793	0.817	54
Week 3	6.568	4.155	37	3.855	2.07	46	2.07	0.897	57
Week 4	6.766	4.297	36	4.297	2.39	44	2.119	1.01	52
Week 5	6.86	3.885	43	3.885	2.043	47	2.043	0.896	56
Week 6	7.329	4.216	42	4.216	2.14	49	2.14	0.855	60

The results analyzed for six sampling times for total phosphorus were demonstrated in the table 10 where the average influent and effluent concentration of TP for Nyarutarama natural hybrid pond were 6.5 and 0.9 mg/L. This indicating the high removal for the whole system. From the table 11 shown the removal efficiencies for ponds and constructed wetland. The average removal efficiencies for primary facultative pond, water lettuce- covered pond and constructed wetland were 39%, 46% and 56% respectively. These results showed that the constructed wetland had high removal efficiency of phosphorus than pond systems as indicated on Fig. 17. This removal of phosphorus was explained by the substrates and macrophytes which were in the CW and water lettuce- covered pond.

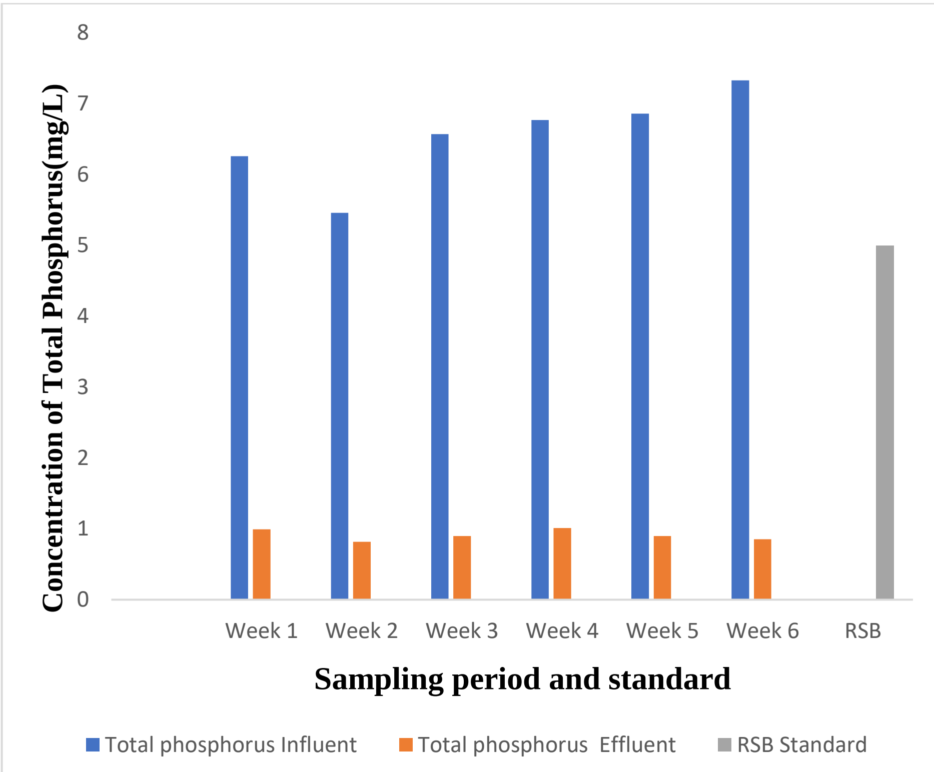

Figure 16: TP measurement

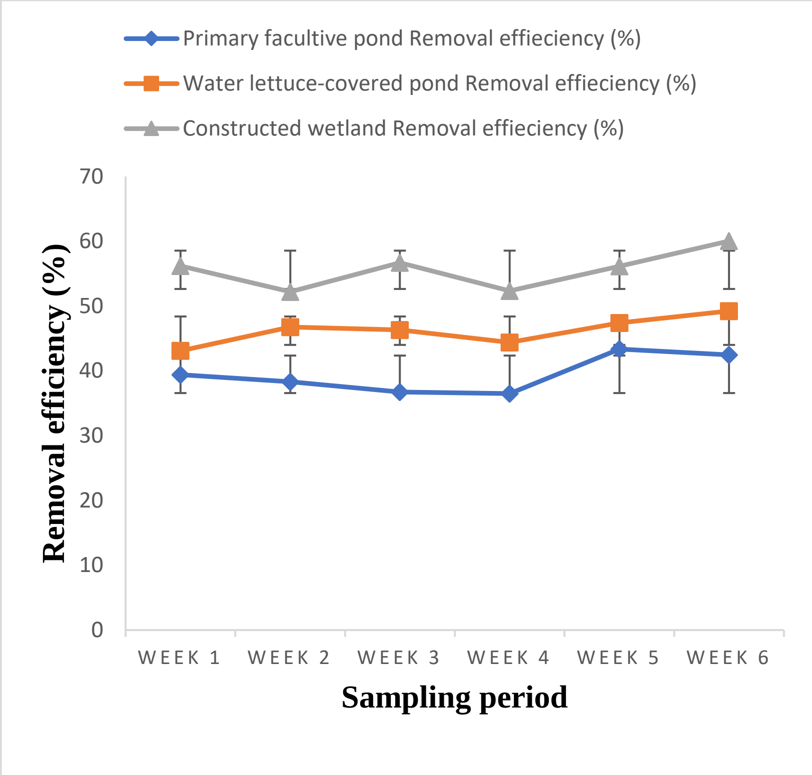

Figure 17: Comparison of removal efficiencies of Total phosphorus of two primary and secondary ponds and constructed wetland

Constructed wetland cannot expect long-term phosphorus removal unless regular plant harvesting is done. Phosphorus is mostly eliminated from a CW via medium adsorption and plant uptake [29]. The soil compartment has been identified as the primary long-term Phosphorous storage pool in most wetland investigations. Temperature has no bearing on phosphorus removal in constructed wetlands. Temperature showed small impact on phosphorus removal, because the prime removal mechanisms such as chemical precipitation and physico-chemical sorption did not depend on temperature [96].

The average effluent concentration of TP was 0.912 mg/L. The result met the discharge standard which was 5mg/L set by Rwanda standard board [26]. The lowest and the highest average removal efficiencies were 39% and 56% for primary facultative pond and constructed wetland respectively. The average RE efficiency for CW compared to the similar study was higher than the removal efficiency reported in Kenya which was 26% [94].

4.1.7. Total coliform

The following table showed the sampling date, concentrations of Total coliform (TC) and the removal efficiency for the primary facultative pond, water lettuce- covered pond and constructed wetland of Nyarutarama hybrid natural pond.

Table 11: Concentrations of Total coliform and their removal efficiencies in Nyarutarama hybrid pond

Sampling date	Unit	Primary facultative pond			Water lettuce-covered pond			Constructed wetland		
		Influent conc. of TC	Effluent conc. of TC	Removal efficiency (%)	Influent conc. of TC	Effluent conc. of TC	Removal efficiency (%)	Influent conc. of TC	Effluent conc. of TC	Removal efficiency (%)
Week 1	10^5 (cfu/100ml)	423	274	35	274	46.7	83	46.7	21.8	53
Week 2	10^5 (cfu/100ml)	442	301	32	301	43	86	43	18.2	58
Week 3	10^6 (cfu/100ml)	200	122.6	39	122.6	15	88	15	6.8	55
Week 4	10^6 (cfu/100ml)	204	131.3	36	131.3	24.8	81	24.8	10.2	59
Week 5	10^5 (cfu/100ml)	280	184	34	184	43	77	18	6.8	62
Week 6	10^5 (cfu/100ml)	264	154.6	41	154.6	26	83	26	9.3	64

***Conc.:** Concentration

The table 11 showed the reduction of total coliforms in Nyarutarama natural hybrid pond. The average removal efficiencies for primary facultative pond, water lettuce-covered pond and constructed wetland were 36%, 83% and 58% respectively. The results indicated that the highly removal efficiencies were in water lettuce – covered pond than in constructed wetland and primary facultative pond as shown in fig.18.

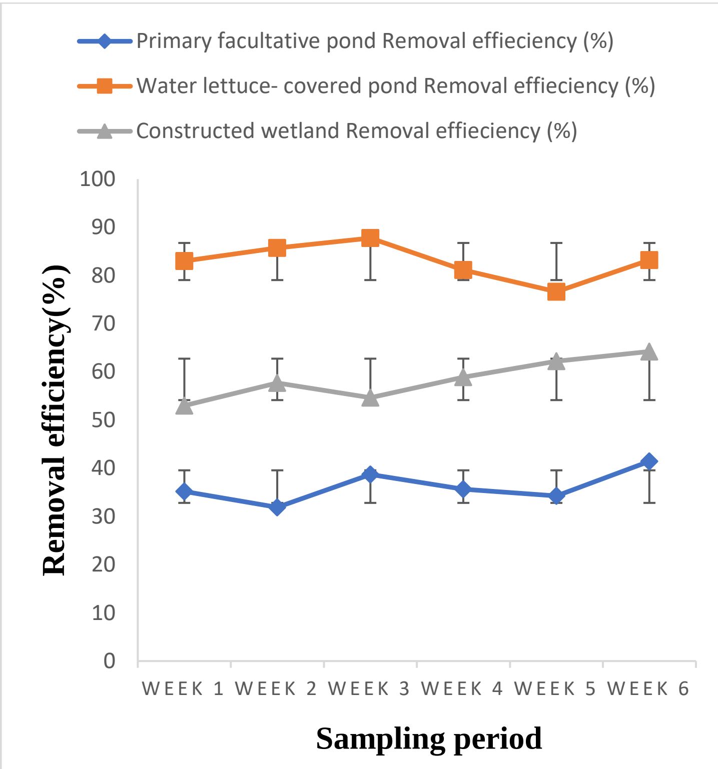

Figure 18: Comparison of removal efficiencies of Total coliform of two primary and secondary ponds and constructed wetland

From the fig. 18 the second pond is highly removing total coliform compared to the primary pond and constructed wetland because this pond was covered by water lettuce which decreased the concentration of DO in that system, this caused the highly dying of coliforms and the removal became high. The average effluent concentration of TC was 3.7x 10^6 cfu/100mL which was very high compared to the standard which was less than 400 cfu/100ml [26], this indicated that the effluent from Nyarutarama natural hybrid pond was very contaminated.

4.1.8. Feacal coliform

The following table shows the sampling date, concentrations of feacal coliform (FC) and the removal efficiency for the primary facultative pond, water lettuce- covered pond and constructed wetland of Nyarutarama hybrid natural pond.

Table 12: Concentrations of feacal coliform and their removal efficiencies in Nyarutarama hybrid pond.

Sampling date	**Unit**	**Primary facultative pond**			**Water lettuce-covered pond**			**Constructed wetland**		
		Influent conc. of FC	Effluent conc. of FC	Removal efficiency (%)	Influent conc. of FC	Effluent conc. of FC	Removal efficiency (%)	Influent conc. of FC	Effluent conc. of FC	Removal efficiency (%)
Week 1	10^5 (cfu/100ml)	258	154	40	154	34.9	77	34.9	16.8	52
Week 2	10^5 (cfu/100ml)	260	149	43	149	29.1	80	29.1	13.1	55
Week 3	10^5 (cfu/100ml)	158	98	38	98	21	79	21	9	57
Week 4	10^5 (cfu/100ml)	284	166	42	166	41	75	41	17.9	56
Week 5	10^5 (cfu/100ml)	194	101.9	47	101.9	10.6	90	10.6	4.58	57
Week 6	10^5 (cfu/100ml)	181.8	93.1	49	93.1	15.2	84	15.2	5.61	63

***Conc.:** Concentration

The results in the table 12 showed that the concentration of feacal coliforms decreased in Nyarutarama natural hybrid pond. The above results showed the average removal efficiencies for primary facultative pond, water lettuce- covered pond and constructed wetland were 43%, 81% and 57% respectively. The fig.20 demonstrated the comparison of removal efficiencies of the two ponds and constructed wetland. This figure indicated that feacal coliforms are highly removed in the second pond than in primary pond and constructed wetland because this pond was covered by water lettuce which decreased the concentration of DO in that system, this caused the highly dying of coliforms and the removal became high. The average effluent concentration of FC was 1.1x 10^6 cfu/100mL which was very high compared to the RSB standards which was less than 400 cfu/100ml [26].

Even when compared to the WHO standard for the safe use of wastewater for unrestricted irrigation (less than 1000cfu/100ml) [97], the effluent concentration of FC in this study was high. This indicated that the effluent from Nyarutarama natural hybrid pond was highly contaminated.

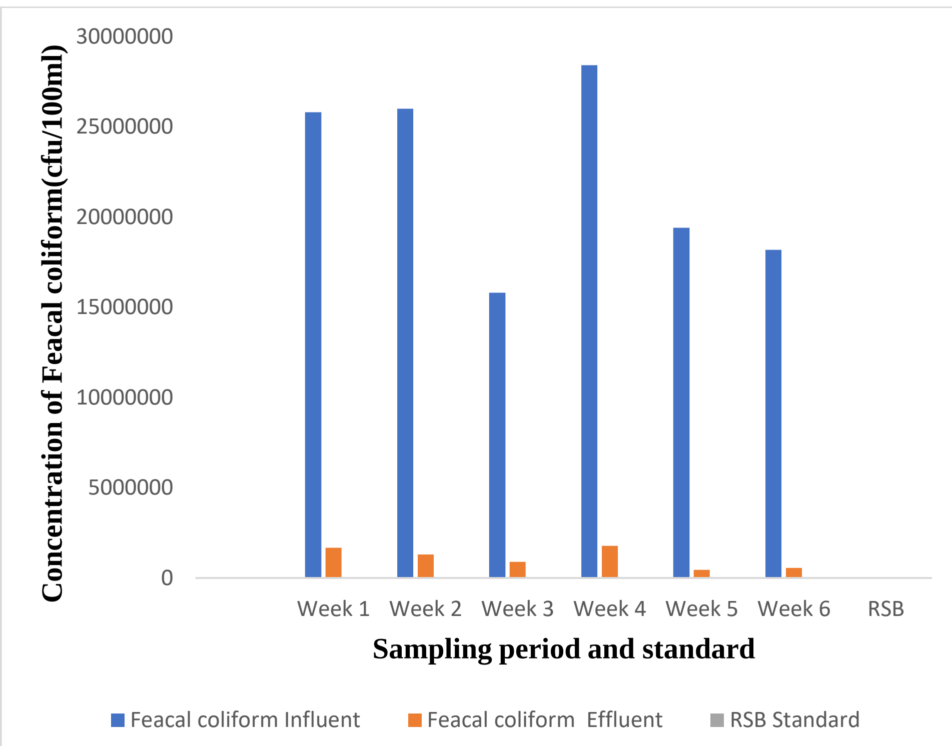

Figure 19: Feacal coliform measurement

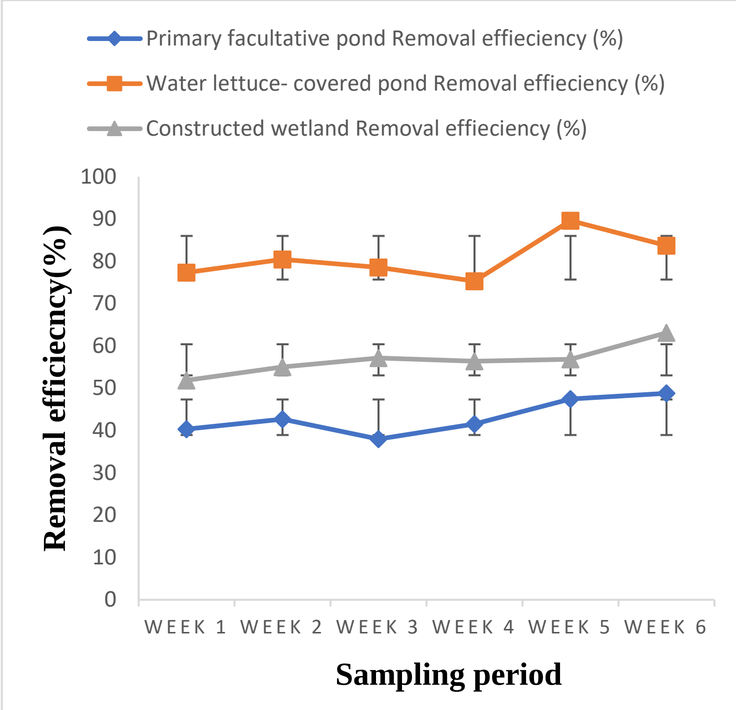

Figure 20: Comparison of removal efficiencies of Feacal coliform of two primary and secondary ponds and constructed wetland.

The results in this study showed the RE in CW was 57% which was lower compared to removal efficiencies reported in Tanzania and Egypt which were 98% and 99.9% respectively [91]. The FC removal efficiency in CW in this study was low. This could be attributed to wetland plants' successful adaption and growth, as well as favorable environmental conditions. The constructed wetland performed well during the maturity period of macrophytes [98]. Macrophytes in Nyarutarama CW were very old due to unharvesting, this could reduce its performance to remove coliforms. But the average removal efficiency of the whole system was 95%, this indicated that the combination of ponds with constructed wetland removal pollutants at high rate.

4.1.9. Escherichia Coli

The following table shows the sampling date, concentrations of Escherichia coli (E. Coli) and the removal efficiency for the primary facultative pond, water lettuce- covered pond and constructed wetland of Nyarutarama hybrid natural pond.

Table 13: Concentrations of Escherichia coli and their removal efficiencies in Nyarutarama hybrid pond

Sampling date	Unit	Primary facultative pond			Water lettuce-covered pond			Constructed wetland		
		Influent conc. of E. Coli	Effluent conc. of E. Coli	Removal efficiency (%)	Influent conc. of E. Coli	Effluent conc. of E. Coli	Removal efficiency (%)	Influent conc. of E. Coli	Effluent conc. of E. Coli	Removal efficiency (%)
Week 1	10^5 (cfu/100ml)	206	133.2	35	133.2	20.9	84	20.9	9.93	52
Week 2	10^5 (cfu/100ml)	260	146	44	146	9.5	93	9.5	3.9	59
Week 3	10^5 (cfu/100ml)	158	101	36	101	12.9	87	12.9	5.8	55
Week 4	10^5 (cfu/100ml)	118	69	42	69	7.67	89	7.67	3.7	52
Week 5	10^5 (cfu/100ml)	129.3	73.4	43	73.4	5.3	93	5.3	2.1	60
Week 6	10^5 (cfu/100ml)	181.8	89.6	51	89.6	5.9	94	5.9	2.23	62

***Conc.:** Concentration

The table 13 demonstrated the concentrations and the removal efficiencies of E. coli in the two ponds and constructed wetland where the RE for primary pond, secondary pond and constructed wetland were 42%, 90% and 57% respectively. As shown on the fig.22 which compared the removal efficiencies of the Nyarutarama hybrid pond where the second pond known as water lettuce- covered pond was highly removing E. coli than primary pond and constructed wetland because it was covered by water lettuce which caused the decrease of DO concentration in that pond and this leaded the dying of E. coli at high rate.

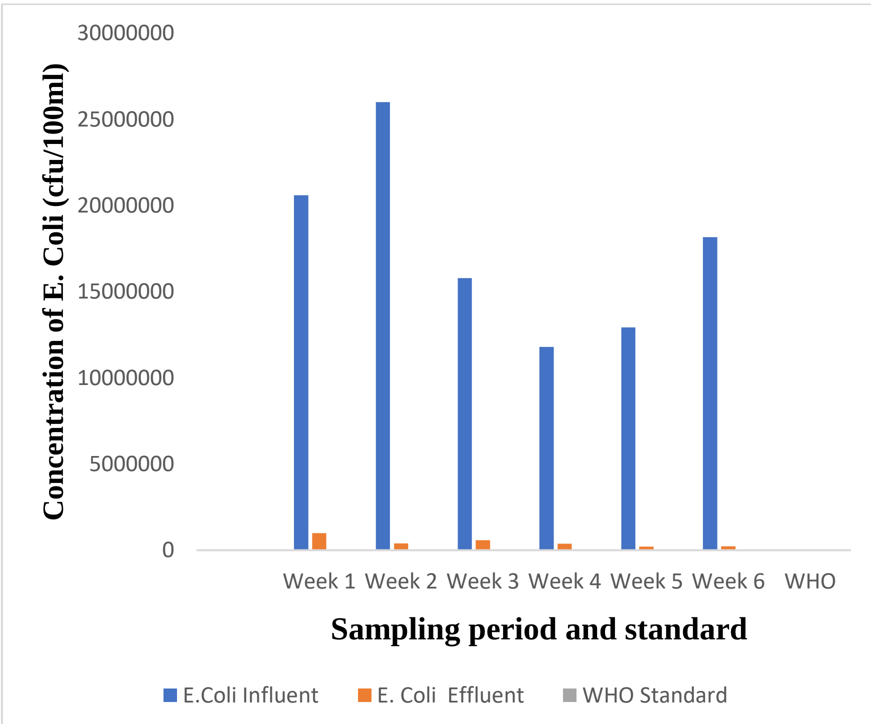

Figure 21: Escherichia coli measurement

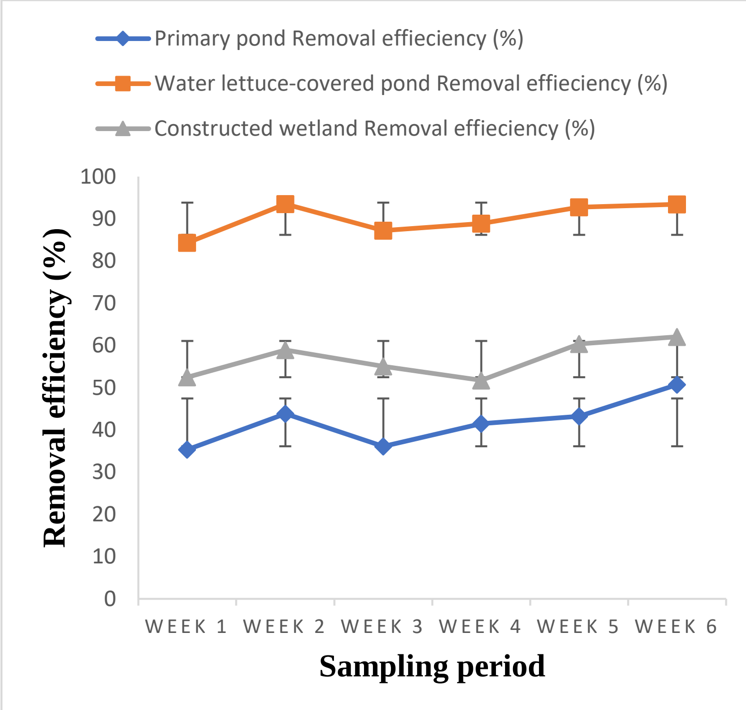

Figure 22: Comparison of removal efficiencies of Escherichia Coli of two primary and secondary ponds and constructed wetland.

The results in the table 14, demonstrated that the average effluent concentration of E. Coli was $5x10^5$ cfu/100ml. This concentration exceeded the effluent standards for wastewater. This indicated that the effluent from Nyarutarama natural hybrid pond was highly contaminated.

The results in this study showed the lowest and the highest E. coli removal efficiencies were 42% and 90% for primary pond and secondary (water-lettuce covered) pond respectively.

The CW of Nyarutarama did not perform well due to the old plants which were not harvested which reduced its performance. The constructed wetland performed well during the maturity period of macrophytes [98].

4.2. Mechanisms of nutrients and pathogens removal in Nyarutarama natural hybrid pond

4.2.1. Nitrogen

4.2.1.1. Ammonification

This mechanism is the biological transformation of organic nitrogen to ammonia. In both the aerobic and anaerobic zones, nitrogen-containing pollutants breakdown quickly, generating ammonium-nitrogen (NH_4-N).

The inorganic NH_4-N primary removed in constructed wetland by nitrification-denitrification processes. Ammonification rates are highest in the anaerobic conditions and reduced when the mineralization circuit transitions from aerobic to facultative anoxic to force anaerobic bacteria. The rates of ammonification are impacted by temperature, pH, available nutrients, and soil structure.

4.2.1.2. Nitrification

It is a wetland decomposition mechanism that are thought to transform the highest organic nitrogen to ammonia. This mechanism is the chemolithoautotrophic oxidation of ammonia to nitrate under stringent aerobic conditions. It occurs in two steps: The first step is the transformation of ammonia to nitrite followed by the second step which convert the produced nitrite into nitrate. The nitrification rate is impacted different factors such as temperature, pH, alkalinity, inorganic carbon source, moisture, microbial population, and concentrations of ammonium–N and dissolved oxygen

4.2.1.3. Denitrification

This mechanism utilizes nitrate as the terminal electron acceptor in hypoxia environments. Denitrification utilized denitrifying bacteria which decline inorganic nitrogen from nitrate and nitrite into nitrogen gas. Denitrification gives energy to denitrifiers and is influenced by the organic matter of the electron[89]. This process is shown in the following equation.

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2 \qquad (5)$$

This process can only occur in systems contain anoxic conditions because dissolved oxygen inhibits the enzyme system needed for the process.

4.2.1.4. Plant uptake

Macrophytes transform inorganic nitrogen forms such as ammonia and nitrate into organic molecules that serve as building blocks for cells and tissues. The rooted plants have the capacity to utilize settled nutrients. Depending on the kinds of nitrogen present in the wetland, different plant species have different preferred mechanisms of nitrogen absorption. The NH_4^+ is frequently preference in macrophytes that live in the environment where nitrification is limited. The rate of intake and storage of nutrients by plants is controlled by the amount of nutrients in their tissues.

4.2.1.5. Adsorption

Ammonia N can be chemisorbed to surface of the substrate material. This process is determined by properties of porous media utilized and the contact time between wastewater with the porous media[56]. When the ammonia concentration in the wastewater decreased due to nitrification, a portion of ammonia will be adsorbed, allowing the equilibrium with the new concentration to be reached.

4.2.2. Phosphorus

4.2.2.1. Soil adsorption and precipitation

Adsorption refers to the transport of soluble inorganic P from soil pore water to soil mineral surfaces, where it accumulates but does not infiltrate the soil surface. The soil ability to absorb phosphorus rises with its clay concentration or mineral components [52]. Phosphate ions can combine with Al, Fe, Ca, or Mg cations to produce new solid precipitates, which can be amorphous or crystalline. Adsorption and precipitation are thought to be intertwined processes, and most studies indicated no distinction between them. The filter medium grain size may impact adsorption; as powdered materials have a greater accessible specific surface area for adsorption however, because of their lower hydraulic conductivity, they are more prone to clogging.

4.2.2.2. Plant uptake

Plants use P presented in the wastewater to meet their growth needs. Plants absorb phosphorus at very low rate than adsorption to the substrate. The large amount of phosphorus is absorbed by plant roots; absorption via leaves and shoots is limited to immersed species and is generally insignificant. The rate of phosphorus uptake by macrophytes is very high at the starting of the growth stage (for young plant) than the mature ones. P is returned from biomass in the wetland after the plant decompose. The removal of P requires harvesting of those macrophytes [52, 56].

4.2.2.3. Microbiological uptake

Microbiological uptake is rapid, but the amount of P stored is minimal. Microbiota absorb nutrients quickly because these organisms develop and replicate quickly. Even though bacteria are commonly thought to be decomposers that only mineralize organic P, they have also been found to control the flux of through the sediment-water interface.

4.2.3. Effects of Sulfate and electrode potential on nutrients removal

Low SO_4^{2-} and electrode potential **(**Eh) make the system to be in anaerobic/anoxic conditions, means that they favour denitrification process which is one of the main mechanism of nutrients removal in constructed wetland. When Sulfate and Eh increase, they favour nitrification where there was the oxidation of nutrients and be removed in the system easily [99].

4.2.4. Pathogens

4.2.4.1. Sedimentation, adsorption, natural die-off

Sedimentation is the main mechanism for pathogens removal in wastewater treatment system. In CW, sediments and media grains can accumulate significant quantities of pathogens, implying that bottom gravel layers could operate as a pathogen sink. Microorganisms adsorb to plant roots, filter media grain or sediments as well as the related biofilm. Adsorption of coliform bacteria is impacted by the size and type of particles attached. The existence of plants is thought to improve the efficacy of CW in pathogen elimination. Because the biofilm's expanded root system and oxygen availability encourage bacteria growth and activity.

4.3. Results and discussion for Key informant interviews

This survey was aimed to get information on how the Nyarutarama hybrid natural pond can be managed in order to continue operate sustainably. During this survey, 21 persons were interviewed. Those interviewed persons are classified into five categories which are citizens from Juru estate, people leave near that treatment systems, local authority, Experts in wastewater treatment systems and hygiene and sanitation officer in WASAC. The obtained results were presented in the table 15.

Table 14: Summary of results for key informant interview

Summarized question	**Strongly disagree**		**Disagree**		**Neither disagree nor**		**Agree**		**Strongly agree**	
	1		**2**		**3**		**4**		**5**	
	n	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
Nyarutarama natural wastewater treatment system does not need regular maintenance.	17	81	4	19	0	0	0	0	0	0
That system needs regular maintenance and management plans	0	0	0	0	0	0	4	19	17	81
I want to pay regularly for sustainable operation and maintenance of that system.	2	10	2	10	0	0	10	48	7	33
Being interested in learning basic skills for sustainable operation and maintenance of that system.	0	0	1	5	7	33	10	48	3	14
Being cooperated with teams rehabilitating that system	0	0	1	5	0	0	15	71	5	24
Permanent and trained staffs should be recruited for management of that system.	0	0	0	0	0	0	7	33	14	67
Measurements of the effluent from that system is needed in a period of six months	0	0	0	0	1	5	12	57	8	38
Lack of regular monitoring may cause the discharge of contaminated water.	0	0	1	5	4	19	11	52	5	24
Lack of awareness to its economic benefits may contribute to its degradation	0	0	6	28	10	48	4	19	1	5
Lack of training for natural wastewater treatment system personnel leads to its poor management.	0	0	0	0	2	10	13	62	6	28
Lack of clear policies on public participation in wastewater management reduces the people awareness in management of that system	1	5	2	10	4	19	10	48	4	19
Agricultural activities carried out on the buffer zones of that system are one of main causes of its degradation	1	5	2	10	1	5	10	48	7	33

***n**: number of people responding.

The table 15 showed many interviewed people said that the Nyarutarama wastewater treatment system needs special management where 81% of interviewed persons responded that, that system need regular maintenance and management plans. The readiness to pay for the sustainable operation and maintenance of that system is low, where only 48% and 33% of interviewee were strongly agree and agree to pay regularly respectively. Among interviewed persons only 48% were agree to be interested in learning basic skills for the sustainable operation and maintenance of the system. So, people who would like to cooperate with WASAC, experts and stakeholders who involved in the rehabilitation of Nyarutarama natural treatment system 71% of interviewee were agree. The permanent and trained staffs should be recruited to oversee the sustainable operation and management of that system where 67% of interviewed ones were strongly agree.

Taking measurements on the effluent of Nyarutarama wastewater treatment system is needed as 57% of interviewee were agree. The lack of regular monitoring sometimes causes the discharge of non-comply regulatory standards for wastewater where 52% of interviewed ones were agree. From the interviewee 48% were neither disagree nor agree and 28% were disagree on misunderstanding on the economic benefits of Nyarutarama natural hybrid pond when it is well managed may cause it to degrade. Lack of training of natural wastewater treatment system personnel leads to its poor management where 62% of interviewed people were agree.

Among interviewed persons, only 48% were agree that the lack of clear policies on public participation in wastewater management reduces the people awareness in management of that system. Also 48% of interviewee were agree that the agricultural activities carried out in buffer zone of Nyarutarama natural treatment system were one of the primary causes of its deterioration. According to the results from key informant interview, the following points were mentioned:

1. Nyarutarama natural treatment system needs regular maintained and management plans but there is a need of awareness rising on people to pay for its sustainable management.
2. People of Juru estate and those live near that system need to cooperate with a team involved in rehabilitation of Nyarutarama natural hybrid pond.
3. The permanent and trained staffs should be recruited to oversee the sustainable operation and management of that system.
4. Regular monitoring and taking measurements of effluent of that system in a period of six months are required.
5. Training on natural wastewater treatment system personnel is required.

6. Clear policies and awareness on public participation on wastewater management are required. In *Official Gazette n°20bis of 14/05/2018;* Regulation N°004/R/SAN-EWS/RURA/2016 OF 10/11/2016 Governing decentralized wastewater treatment systems, its article 19 is: Requirements for wastewater treatment system maintenance, Article 21: Operation and maintenance manual and Article 24: Monitoring of wastewater treatment system performance. There is a need of public participation policies on wastewater.
7. Agricultural activities cannot be carried out in the buffer zone of natural treatment system.

4.4. Limitation of hybrid natural pond treating municipal wastewater

Even though the hybrid natural treatment systems for treating wastewater are more effective and environmentally friendly but their use have limitations. Those are:

- They usually require large surface area than the conventional wastewater treatment systems. Only where land is available and affordable can hybrid natural treatment be cost-effective compared to other systems.
- Seasonal variability, as a result of shifting environmental conditions such as rainfall and drought. It's possible that the performance may be less compatible than with conventional treatment.
- Sensitivity of harmful substances like pesticides and ammonia to biological components
- Pollution flushes or surges in water flow might limit treatment effectiveness temporary
- Inadequate attention to operation and maintenance may led to the systems malfunctioning and falling out of use [100].

4.5. Methods to be applied for sustainable operation and maintenance of natural wastewater treatment system in highly urbanized region.

The following methods should be applied in the region with highly urbanized for sustainable operation and maintenance of natural wastewater treatment systems.

4.5.1. Preliminary treatment

This is required installation of the system for screening and grit removal at inlet i.e., removing the large solid particles and also use standard septic tanks to facilitate sedimentation. The regular desludging of septic tanks is required in order to avoid the clogging of the system. This will contribute in the sustainable operation of the wastewater treatment system.

4.5.2. Awareness raising for willingness to pay

This method is crucial because people generating wastewater need to have a contribution for the sustainable operation and maintenance, also the local authorities should intervene and get training on the important benefits of a well-maintained natural wastewater treatment systems. According to the responses from key informant interview, many people understand the importance of natural treatment system but some of them think that the sustainable management of the system should still be part of the government or other competent authority. Social mobilization and awareness on maintenance of the system are needed in to show the contribution of each beneficiary. To achieve these, require awareness by demonstrating the environmental and economic benefits of a well-maintained natural wastewater treatment systems.

4.5.3. Improvement of the treatment systems area for their valorization.

This kind of treatment system when operate well the effluent can be used in different activities such as irrigation, construction works and car wash etc. When they are well designed and maintained, they can also be used as, landscape enhancement, wildlife habitat, recreational and educational activities[49]. Therefore the improvement and well maintenance of the system can generate income which can help to implement many different natural treatment system as the urban regions generate a huge amount of wastewater and require to increase the treatment systems.

4.5.4. Permanent and trained staffs to oversee the system operation and maintenance

The permanent and trained staffs will play a key role in the sustainable operation of the treatment system because, they will have a role of observe day to day each change happen to the system and try to resolve the issue directly and the system continue to operate properly.

Also, this team of staffs will involve in monitoring the system performance by collecting the representative samples once every six months as stated in *Official Gazette n°20bis of 14/05/2018;* Regulation N°004/R/SAN-EWS/RURA/2016 OF 10/11/2016 Governing decentralized wastewater treatment systems, Article 24 of Monitoring of wastewater treatment system performance and measure some physico-chemical and bacteriological parameters.

Chapter 5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

The use of effective, low-cost, less-energy-intensive, and readily operated secondary wastewater treatment systems is a major concern in Rwanda, where the release of untreated wastewater into the planet's surface accumulating water is usually applied in largest areas of the country. It is vital to safeguard the environment and public health, and it can also open up the possibility of re-use treated wastewater for various activities such as irrigation, building, and car wash.

The following conclusions are drawn from research:

1. The nitrogen removal rate in ponds and constructed wetland was not very high due to the environmental conditions of each compartment. NH_4-N was highly removed than other nitrogen forms and TN was the lowest removed. Each compartment of Nyarutarama hybrid natural pond did not show the highest removal efficiency only CW due to the substrates and macrophytes. So, the used of hybrid system increase the removal efficiency of nitrogen forms.
2. The removal efficiency for all phosphorus forms was moderate. The CW showed high RE than pond. This was due to their substrates such as soil which adsorbed it and plants which uptake during their growth. The combination of ponds and CW showed the best RE.
3. The system showed the high removal of coliforms except in primary pond. The highest removal was in secondary pond covered by water lettuce which declined the DO and cause bacteria to die at high rate.
4. All nutrients analyzed in this study comply the national and international standards for effluent of wastewater but the effluent for coliforms exceeded the standards.
5. The mechanisms which involved in the removal of nutrients and pathogens in Nyarutarama natural hybrid system were mainly: sedimentation, Plant uptake, adsorption, natural die-off, nitrification and denitrification.
6. Hybrid natural ponds treating municipal wastewater showed the main limitation of requiring large land area which is not easy to get it in urbanized region. Also, the season variability limits the performance of those system.
7. The willingness for people to reward for the sustainable functioning and sustentation of the treatment system was at 48% of all interviewed persons.
8. Preliminary treatment, awareness raising for willingness to pay, improvement of the treatment system area and use of permanent trained staffs are the methods to be applied for sustainable operation and maintenance of natural treatment systems.

5.2. Recommendations

The following recommendations are made from the results of this research:

1. To achieve optimal development and increased pollution removal effectiveness, desludge periodically and appropriate control of macrophyte coverage, including an adequate macrophyte harvesting strategy, are required.
2. Regularly inspecting outlet quality by practical analysis of important parameters that are toxic to the environment particularly nutrients and feacal coliforms.
3. Improve the treatment systems in order to meet the effluent standards.
4. Awareness raising for willingness to pay is highly required
5. Valorization of natural wastewater treatment systems for touristic and research area.
6. Permanent and trained staffs to oversee the maintenance and operation of the systems.
7. If the management will not be changed, the rehabilitated Nyarutarama treatment system after five years will be degraded. There is a need to improve the management system in terms of maintenance and operation.

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APPENDICES

Appendix A: Results of physico-chemical parameter

A.1. pH

Sampling date	Primary facultative pond		Water lettuce-covered pond		Constructed wetland	
	Influent pH	Effluent pH	Influent pH	Effluent pH	Influent pH	Effluent pH
16-Sep-21	6.39	6.15	6.15	6.1	6.1	6.19
23-Sep-21	7.66	6.83	6.83	6.69	6.69	7.11
30-Sep-21	7.81	6.75	6.75	6.79	6.79	7.03
7-Oct-21	6.18	6.48	6.48	6.58	6.58	7.07
14-Oct-21	7.69	7.1	7.1	7.27	7.27	7.96
21-Oct-21	7.7	7.73	7.73	7.95	7.95	8.85

A.2. Temperature

Sampling date	Primary facultative pond		Water lettuce-covered pond		Constructed wetland	
	Influent Temperature	Effluent Temperature	Influent Temperature	Effluent Temperature	Influent Temperature	Effluent Temperature
16-Sep-21	24.9	22.9	22.9	27.2	27.2	30.1
23-Sep-21	26.6	23.9	23.9	25.7	25.7	29.9
30-Sep-21	25.1	21.6	21.6	21.4	21.4	23.8
7-Oct-21	27.5	22.3	22.3	22.2	22.2	30.5
14-Oct-21	25.6	23.2	23.2	22.9	22.9	27.1
21-Oct-21	23.7	24	24	23.5	23.5	23.6

A.3. Dissolved oxygen

Sampling date	Primary facultative pond		Water lettuce-covered pond		Constructed wetland	
	Influent DO	Effluent DO	Influent DO	Effluent DO	Influent DO	Effluent DO
16-Sep-21	0.94	2.3	2.3	5.86	5.86	8
23-Sep-21	0.28	1.45	1.45	0.94	0.94	7.87
30-Sep-21	2.52	1.44	1.44	0.78	0.78	4.02
7-Oct-21	2.91	1.49	1.49	1.02	1.02	10.3
14-Oct-21	2.44	4.4	4.4	4.13	4.13	8.77
21-Oct-21	1.98	7.32	7.32	7.23	7.23	7.26

A.4. Electrical conductivity

Sampling date	Primary facultative pond		Water lettuce-covered pond		Constructed wetland	
	Influent EC	Effluent EC	Influent EC	Effluent EC	Influent EC	Effluent EC
16-Sep-21	784	253	253	454	454	333
23-Sep-21	1251	557	557	497	497	400
30-Sep-21	1232	617	617	594	594	438
7-Oct-21	808	401	401	461	461	513
14-Oct-21	907	402	402	439	439	451
21-Oct-21	1006	404	404	418	418	382

Appendix B: Questionnaire

UNIVERSITY OF RWANDA- COLLEGE OF SCIENCE AND TECHNOLOGY- SCHOOL OF SCIENCE-DEPARTMENT OF CHEMISTRY

Evaluation of nutrients removal and typologies for successful operation and maintenance for hybrid natural pond treating municipal wastewater in Kigali

A CASE STUDY OF NYARUTARAMA HYBRID NATURAL PONDS

Date of interview/ itariki y'ikiganiro……………………

I. IDENTIFICATION OF RESPONDENT/UMWIRONDORO W'USUBIZA

1)Age/imyaka: ………………, 2)Sex/igitsina: …………

3) Function/icyo akora ………………… 4) Institution/ikigo(urwego).................

II. QUESTIONNAIRE/IBIBAZO

Please rate (✓) your agreement with each of the following items from 1 (strongly disagree) to 5 (strongly agree)/ Nyamuneka gereranya (✓) amasezerano yawe na buri kintu gikurikira kuva 1 (kutemeranya cyane) kugeza kuri 5 (kwemeranya cyane).

Research Question/ ikibazo cy'ubusha-kashatsi	Item/ Ingingo	Strongly Disagree/kutemeranya cyane	Disagree/kutemeranya	Neither disagree nor agree/ kutabihakana no kutemeranya	Agree/kwemeranya	Strongly agree/Ndemeranya cyane
		1	2	3	4	5
Sustainable operation and maintenance/ Imikorere irambye no kuyitaho	I feel like the Nyarutarama natural wastewater treatment systems do not need regular maintenance, the nature will always find a solution/ Ndumva nka sisitemu yo gutunganya amazi mabi ya Nyarutarama idakeneye kubungabungwa buri gihe, kamere izahora yishakira igisubizo.					
	I feel like that system need regular maintenance and management plans/ Ndumva iyo sisitemu ikeneye kubungwabungwa buri gihe na gahunda y'imicungire yayo.					

	I want to regularly pay for the sustainable operation and maintenance of the Nyarutarama natural wastewater treatment systems/ Nifuza kwishyura buri gihe kugira ngo iyi sisitemu y'umwimerere yo gutunganya amazi mabi ya Nyarutarama ikomeze gukora no kubungwabungwa neza muburyo burambye					
	I am interested in learning basic skills for the sustainable operation and maintenance of the system/ Nshishikajwe no kugira ubumenyi bw'ibanze kubyerekeye imikorere irambye no kubungabunga sisitemu.					
	I would like to cooperate with WASAC, experts, and stakeholders involved in the rehabilitation of the Nyarutarama natural treatment system/ Ndifuza gufatanya na WASAC, impuguke, n'abafatanyabikorwa bagize uruhare mu gusana sisitemu y'umwimerere itunganya amazi mabi ya Nyarutarama					
	I feel that permanent and trained staffs should be recruited to oversee the sustainable operation and management of the Nyarutarama water treatment system/Numva hashyirwaho abakozi bahoraho kandi babyigiye bashinzwe gukurikirana mu buryo buhoraho imikorere n'imicungire ya sisitemu itunganaya amazi mabi ya Nyarutarama					
	I feel the need to take measurements on the wastewater treated by the Nyarutarama system which is sent to the environment for a period of six months/Numva hakenewe kujya hafatwa ibipimo ku mazi yatunganyijwe na sisitemu ya Nyarutarama yoherezwa mu bidukikije mu gihe cy'amezi atandatu.					
Existing challenges/gaps: Ibibazo biriho / icyuho	I feel that lack of the regular monitoring may cause the discharge of non- comply regulatory standards for wastewater/ Ndumva kubura kw'igenzura rya buri gihe bishobora gutera gusohora amazi atujuje ibipimo bigenga amazi mabi yoherezwa mu bidukikije.					
	I see that the degradation of Nyarutarama natural wastewater treatment system is due to the lack of awareness to its economic benefits/ Njye mbona iyangirika rikabije ry'iyi sisitemu y'umwimerere ya Nyarutarama itunganya amazi mabi riterwa no kutamenya inyungu z'ubukungu zayo mu gihe yitaweho neza.					
	I feel like the lack of training of natural wastewater treatment system personnel leads to its poor management/ Numva ibura ry'amahugurwa y'abakozi ba sisitemu yo gutunganya amazi mabi bitera imicungire yayo mibi.					
	I think that the lack of clear policies on public participation in wastewater management reduces the people awareness in management of wastewater treatment system/ Ntekereza ko kutagira					

	ingamba ziboneye zigaragaza uruhare rw'umuturage mu micungire y'amazi mabi bigabanya imyumvire ye mu micungire ya sisitemu yagenewe kuyatunganya.					
	I think the agricultural works that are carried out on the outskirts of this system are one of the main causes of its degradation/Ntekereza ko imirimo y'ubuhinzi ikorerwa mu nkengero z'iyi sisitemu ari imwe mu bituma yangirika cyane					