ASSESSMENT OF EFFICIENCY OF FINLAYS SAOSA CONSTRUCTED WETLAND FOR TREATING TEA EXTRACT WASTEWATER IN KERICHO, KENYA

Master of Science Thesis

by

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DECLARATION AND RECOMMENDATION

Declaration

This thesis is my original work and has not been presented for examination in any institution.

Signature: ____________________ **Date:** 12-10-2025

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Recommendation

This thesis has been submitted for examination with the approval of our university supervisors.

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DEDICATION

To my entire family, together with my friends, for their selfless support and encouragement to see me go through my master’s program.

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ABSTRACT

The release of partially treated tea extract wastewater poses serious environmental risks due to high pollutant loads, necessitating sustainable treatment solutions, such as constructed wetlands. Additionally, there is no published data on the operational efficacy of Finlays Saosa constructed wetland. Therefore, this study assessed the efficiency of Finlays Saosa constructed wetland for treating tea extract wastewater in Kericho, Kenya, from November 2024 to March 2025. Water samples were collected twice a month from seven sampling points and analyzed in the laboratory at the Department of Biological Sciences, Egerton University. American Public Health Association (APHA, 2017) Standard Procedures was used to analyze BOD, COD, NH_4^+, TSS, tannin, TN, TP, SRP, NO_3^-, and NO_2^-, while parameters like pH, EC, DO, and water temperature were measured *in situ* using a calibrated multi-meter model HQ 40D (HACH). Above-ground biomass of macrophytes was determined by the harvest method, while nutrient allocation in the ground sample was estimated calorimetrically after acid digestion. Data was processed using IBM SPSS software version 28 and Microsoft Office Excel 2007, subjected to a normality test using the Shapiro test and homogeneity of variance using the Levene Test. ANOVA showed significant variation in physical, chemical, and nutrient parameters ($p<0.05$) except for DO. Additionally, Tukey's HSD post hoc test differentiated between the groups of means across the sampling location. A t-test compared the mean loadings and concentrations in the inlet and outlet of the constructed wetland. On the other hand, descriptive statistics presented data about the physical, chemical, nutrient parameters, above-ground biomass, nutrient removal, vegetation cover, and removal efficiency. *Pontederia cordata* achieved the highest above-ground biomass (8986.01 ± 2.21 g/m^2) and nitrogen removal rate (62.9 g/m^2), while *Colocasia esculenta* recorded the highest phosphorus removal rate of 17.49 g/m^2. Canna *indica* had the lowest above-ground biomass (2592.13 ± 4.28 g/m^2) and phosphorus uptake (4.15 g/m^2), while *Phragmites mauritianus* recorded the lowest nitrogen uptake (5.75 g/m^2). The constructed wetland showed a high removal efficiency for most pollutants with over 90% removal rate. TSS, TP and BOD_5 met the National Environment Management Authority (NEMA) set standards. However, effluent concentrations of COD and TN did not meet NEMA set standards. The findings will provide practical insights for tea factories in improving their wastewater management and guide wetland designers in selecting efficient macrophytes for nutrient removal, thereby enhancing the operation and maintenance of the constructed wetland.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of variance
BOD	Biological oxygen demand
CER	Cooperate Environmental Responsibility
CIDP	County Integrated Development Plan
COD	Chemical oxygen demand
CSR	Corporate Social Responsibility
CW	Constructed wetland
DO	Dissolved oxygen
FWS	Free water surface flow
FTEK	Finlays Tea Extract (Limited) Kenya
HLR	Hydraulic loading rate
HRT	Hydraulic retention time
HSSF	Horizontal subsurface flow
LWM	Limnology and Wetland Management
N	Nitrogen
NACOSTI	National Council for Science, Technology, and Innovation
NH_4^+	Ammonium
NEMA	National Environment Management Authority
NO_2^-	Nitrite
NO_3^-	Nitrate
P	Phosphorus
SDG	Sustainable development goals
SF	Surface flow
SRP	Soluble reactive phosphorus
SSF	Subsurface flow
TN	Total Nitrogen
TP	Total Phosphorus
VSSF	Vertical subsurface flow wetland

CHAPTER ONE

INTRODUCTION

1.1 Background information

Agro-industrial sectors form a pillar for many economies globally, and they are crucial for employment generation, foreign exchange revenues, and rural development, particularly in developing nations (Bermúdez *et al*., 2024). In Kenya, the tea sector is critical, as it is one of the primary export commodities and a substantial source of income for many (Gesimba *et al*., 2005). Finlays Saosa, a large-scale tea factory in Kericho County, supplies tea in both high quantity and quality to domestic and global markets, meeting a wide range of consumer demands (Finlays, 2016). However, tea processing effluent contains nutrient-rich organic compounds, caffeine, polyphenols, suspended particles, and other contaminants that accumulate in bodies of water, resulting in biodiversity loss, eutrophication, and public health consequences (Kiongo *et al*., 2021). Furthermore, the effluent released into the environment may not meet the standards set by the National Environment Management Authority (NEMA).

Traditional wastewater treatment technologies, like the use of conventional wetlands, are popular in urban areas but not in rural or low-income areas due to excessive costs of installation and maintenance, unaffordable skilled labour, and high energy requirements (Manikandan *et al*., 2022). In recent decades, the use of constructed wetlands has emerged as a nature-based solution for treating both industrial and municipal wastewater (Vymazal, 2007). This engineering system mimics the functions of natural wetlands by using components such as macrophytes, water columns, microbes, and substrate, effectively treating wastewater through physical, chemical, and biological treatments (Vymazal, 2011). They have numerous benefits, including low operation and construction costs, and a sustainable and eco-friendly option for treating industrial discharge before release to the surroundings (Makopondo *et al.,* 2020). However, there is still a gap in the effective treatment of the tea extract effluent using wetlands. While the constructed wetlands have been used to regulate the tea effluents, mostly in East Africa, there was a need for Corporate Environmental Responsibility (CER), as emphasized by Sigma Earth (2024), encouraging companies to adopt sustainable practices that decrease environmental damage. Industries are required to meet environmental standards and use treatment methods that enhance environmental sustainability, and this is part of their Corporate Social Responsibility (CSR) obligations. The efficacy of the constructed wetlands, therefore, will not only improve the environmental goals but also enhance the compliance of the company or industry.

Despite their growing adoption, the efficacy of a constructed wetland varies depending on design, hydraulic loading rate, maintenance, plant species, seasonal variation, and wastewater characteristics (Kadlec and Wallace, 2008). This highlights the importance of assessing the efficiency of specific sites, especially for areas that are less researched, such as East Africa, where field-based data is limited. Evaluating the effectiveness of constructed wetlands not only ensures compliance with environmental regulations but also informs optimization techniques for better performance (Javeed *et al*., 2025).

Finlays Saosa tea factory in Kericho, Kenya, has implemented a constructed wetland system that treats tea extract wastewater before release to the surrounding area. However, there is no published evidence on how effective the system is in eliminating major contaminants, such as tannins, under real-world situations. Evaluating this system's treatment efficiency is crucial for assessing its performance and identifying areas that need improvement. This study will help to advance the larger goals of sustainable industrial practices, protecting the environment, and integrated water resource management (Finlays, 2016).

This research aimed to assess the effectiveness of Finlays Saosa constructed wetland in treating tea extract wastewater to improve wastewater management in the agro-industrial sector. The findings will benefit not only Finlay Saosa and other tea processors in the region but will also help with maintenance, operation, design, policy decision-making, and supporting sustainable agricultural practices, thereby lowering industrial pollution on a local and global level.

1.2 Statement of the problem

Wastewater from the Finlays tea factory contains elevated levels of pollution indicators, such as total suspended solids and chemical oxygen demand, which must be treated to comply with NEMA discharge regulations before being released into the environment. Although constructed wetlands are being advocated as a sustainable and cost-effective wastewater treatment alternative, their efficiency in treating tea extract wastewater under long-term and variable operation conditions remains inadequately assessed. On the other hand, Finlays Saosa CW has been operating for a long time, but there is a lack of documentation and performance data, particularly addressing the removal efficiency of resistant pollutants such as tannins, therefore, raising serious concerns about the system's reliability and adherence to environmental regulations. The disposal of partially treated effluent by CWs leads to wastewater pollution and public health risks, especially to people who do not have access to properly treated water. This issue of lack of documentation is not unique in Finlays Saosa but also reflects widespread gaps in CW performance monitoring in Africa and globally. Addressing these gaps through systematic evaluation and research will generate scientific knowledge that advances understanding of pollutant removal dynamics, improve wetland design and management, and inform policy for sustainable wastewater treatment, thereby contributing to both ecological protection and socio-economic well-being.

1.3 Objectives

1.3.1 General objective

To promote sustainable water resource management through the evaluation of the performance of the constructed wetland system in treating tea extract wastewater.

1.3.2 Specific objectives

i. To determine spatial variation in the physical, chemical, and nutrient parameters along the wastewater treatment pathway.

ii. To quantify the nutrient storage capacity in the macrophyte above-ground biomass and evaluate the potential of different macrophytes for nutrient removal in Finlays Saosa constructed wetland.

iii. To determine the efficiency of Finlays Saosa constructed wetland in treating pretreated tea wastewater in different cells.

1.4 Hypotheses (H_o)

i. The physical, chemical, and nutrient parameters at Finlays Saosa constructed wetland do not change significantly along the wastewater treatment pathway.

ii. There is no significant difference in nutrient storage capacity and in the potential for nutrient removal by different macrophytes at Finlays Saosa constructed wetland.

iii. There is no significant variation in the treatment efficiency of the constructed wetland at Finlays Saosa in treating pretreated tea extract wastewater in different cells.

1.5 Justification

The goal of Kenya Vision 2030 is to transform the country into a newly industrializing, middle-income country that delivers a decent quality of life to all residents in a clean and secure environment by 2030. Using CWs to treat tea extract wastewater supports this vision by promoting sustainable water resource management. This approach aligns with Kenya's Big 4 Agenda under the Fourth Medium Term Plan, particularly the pillars of universal health care and manufacturing, by enhancing public health, supporting environmentally responsible industrial processes, and introducing green manufacturing technology. Furthermore, CWs contribute directly to achieving sustainable development goals, such as access to clean water and sanitation (SDG 6), economic growth and innovation (SDG 8), and responsible production and consumption (SDG 12), through pollution reduction and improved water quality. The initiative also supports local priorities as outlined in the Kericho County Integrated Development Plan (CIDP) by promoting local waste disposal and advancing nature-based treatment solutions. Furthermore, this study reflects Kenya's constitutional commitment to environmental protection as outlined in Article 42 of the Kenyan Constitution of 2010, which guarantees everyone the right to a clean and healthy environment, including access to clean and safe water in adequate quantities. This is mostly relevant to downstream communities located within the vicinity of the factory, whose livelihoods and health depend on the quality of the water resource. In addition, Article 69(1)(g) requires the state to eliminate environmentally damaging processes and activities, thereby underscoring the importance of ensuring that industrial wastewater treatment practices do not compromise community well-being and the integrity of the environment. Therefore, by examining the treatment efficiency of CW at Finlays Saosa tea factory, this research contributes to environmental compliance, identifies effective macrophytes for nutrient removal, and explores long-term cost-effective treatment strategies. The findings aim to inform about improved CW design, operation, and maintenance, as well as serve as a model for sustainable wastewater management in agro-industrial facilities.

1.6 Scope /Limitation of the study

The research was only conducted in Finlays Saosa-constructed wetland in Kericho, Kenya. Additionally, research took place between November 2024 and March 2025, which was a single-season sampling during the dry period. Notably, the study was limited to determining spatial variations in physical, chemical, and nutrient parameters, assessing the nutrient removal capacity of various macrophytes, and evaluating the wastewater treatment effectiveness of constructed wetlands in Finlays Saosa. On the other hand, wastewater from the constructed wetland passed through the soak pit before flowing to the Saosa River, hence there was no certainty about the quality of water released to the river. The study was limited by seasonal fluctuations in pollutant loads, changes in the growth cycle of the dominant macrophytes, the environmental conditions that can affect the constructed wetland performance, short sampling time (twice every month), inadequate finances, unexpected events, and limitations on existing data on macrophytes' nutrient uptake.

1.7 Definition of terms

Constructed wetland: Engineering ecosystems designed to mimic natural wetlands using components such as substrates, wetland plants, microbial populations, and water columns to treat wastewater physically, chemically, and biologically to improve wastewater quality.

Efficiency: This refers to the percentage reduction of pollutants between the influent and effluent of a constructed wetland system.

Macrophytes: Aquatic plants used in constructed wetlands to remove pollutants through processes such as nutrient uptake, oxygen release, formation of zones for microorganism attachment, and support of microbial habitats.

Tea extract wastewater: It is the wastewater generated from the extraction and processing of tea, characterized by high concentrations of coloured compounds like tannins, nutrients, and non-dissolved solids.

CHAPTER TWO

LITERATURE REVIEW

2.1 Constructed wetland

Wetlands are ecosystems that may be natural or artificial, permanently or seasonally flooded, and include fens, marshes, peatlands, or water bodies. They are characterized by hydrophytic vegetation, hydric soil, microbial communities, and animals adapted to this environment containing water that may be static, flowing, fresh, salty, or brackish, and can include marine areas where the depth of the low tide does not exceed six metres (Ramsar Convention Secretariat, 2013). They can be either human-caused or natural, performing distinct functions such as flood management, water purification, and providing aesthetic value.

Constructed wetlands (CWs) are engineered ecosystems that mimic natural wetlands, utilizing components such as substrates, wetland plants, microbial populations, and water columns to treat wastewater physically, chemically, and biologically, thereby enhancing water quality sustainability and cost-effectiveness (Hassan *et al.*, 2021). Ghangrekar *et al.* (2024) highlight that compared to conventional wastewater treatment, CWs are beneficial in that they are eco-friendly, cost-effective, simple to maintain, adaptable to changing hydrological and contaminant loading rates, offer green habitat space, and integrate wastewater reuse for irrigation and aquaculture (Manikandan *et al.*, 2022). On the other hand, CW is limited because it requires a large area to operate; hence, it is not ideal for use in urban areas. Additionally, design criteria for different wastewater and climate conditions are still under development (Sousa *et al.*, 2024).

2.2 History of constructed wetlands and distribution

Constructed wetlands have been utilized globally since the late 1960s, ranging from temperate Europe to tropical Asia and Africa (Vymazal, 2011). It has been used globally to treat wastes of different scales, configurations, and designs (Vymazal, 2011). Most wetlands are subsurface flow wetlands in rural areas, with funding from the European Union for water management initiatives (UN-HABITAT, 2008). On the other hand, the effectiveness of the constructed wetlands depends on wastewater characteristics, climate, and vegetation types (Islam *et al.*, 2022).

In tropical regions such as Africa and Asia, CWs are more effective due to prolonged plant growth and increased microbial activity due to exposure to elevated temperatures

(Kaseva, 2004). China and India use CWs more frequently to address water pollution (Yang *et al*., 2024), while the United States and Canada have constructed wetlands for storm water and agricultural runoff treatment (Hansen *et al*., 2021).

The usage of constructed wetland has increased for sustainable water management, especially in agricultural and tea industries and in developing countries for treating household and industrial wastewater because of its low cost and easy operation (Mburu *et al*., 2013), but research gaps of lack of information on its usage exist, particularly in tropical areas (Chen *et al*., 2024). Additionally, optimizing CW design for specific applications is challenging due to a lack of awareness, limited knowledge, financial constraints, and poor technical support (Makopondo *et al*., 2020). CW's drawbacks, such as clogging by sediments, can limit its application and long-term survival, especially in environments with high organic loads (Vymazal, 2011).

Constructed wetlands are becoming popular in Kenya as a cost-effective and sustainable wastewater treatment option, especially in places with limited access to conventional treatment methods (Aquadocs, 2006). In the hospitality sector, they are commonly used to treat huge volumes of wastewater in hotels, lodges, and resorts, particularly in arid areas, thus promoting environmental conservation (Makopondo *et al*., 2020). Additionally, Finlays Saosa tea factory manages wastewater sustainably, using CWs with macrophytes to reduce pollution indicators like COD (Moshi, 2015).

Furthermore, CWs have been employed at a variety of Kenyan sites, including Abira’s (2008) experimental wetland at the Pan Paper Mill, which proved the use in an industrial setting. Furthermore, some big farms surrounding Lake Naivasha, like the Oserian and Homegrown, have used CWs to control wastewater, reducing lake pollution and fostering sustainable horticulture (Kimani, 2012). On the other hand, tea plantations in the Nandi Hills use CWs to treat tea factory effluents, resulting in cleaner water discharge and potential water reuse (Gituku *et al.,* 2015).

Grey water has been treated by constructed wetlands in the peri-urban setting, giving opportunity for water reuse and resource recovery in areas with no centralized treatment plant (Kilingo *et al*., 2021). Studies have revealed the potential use of CWs in public institutions such as schools and hospitals, assisting in reducing environmental effects (Kilingo *et al.,* 2021). It boosts the tea industry, reduces environmental degradation, improves wastewater treatment, creates jobs, and alleviates poverty (Aquadocs, 2006). Despite limited resource access, family generations influence resource sharing in tea plantations, and increased populations indicate future economic growth (Aquadocs, 2006). In general, CWs are versatile and adaptive, therefore being used in a wide range of wastewater management applications across Kenya, with advantages in environmental health, biodiversity conservation, and sustainable development.

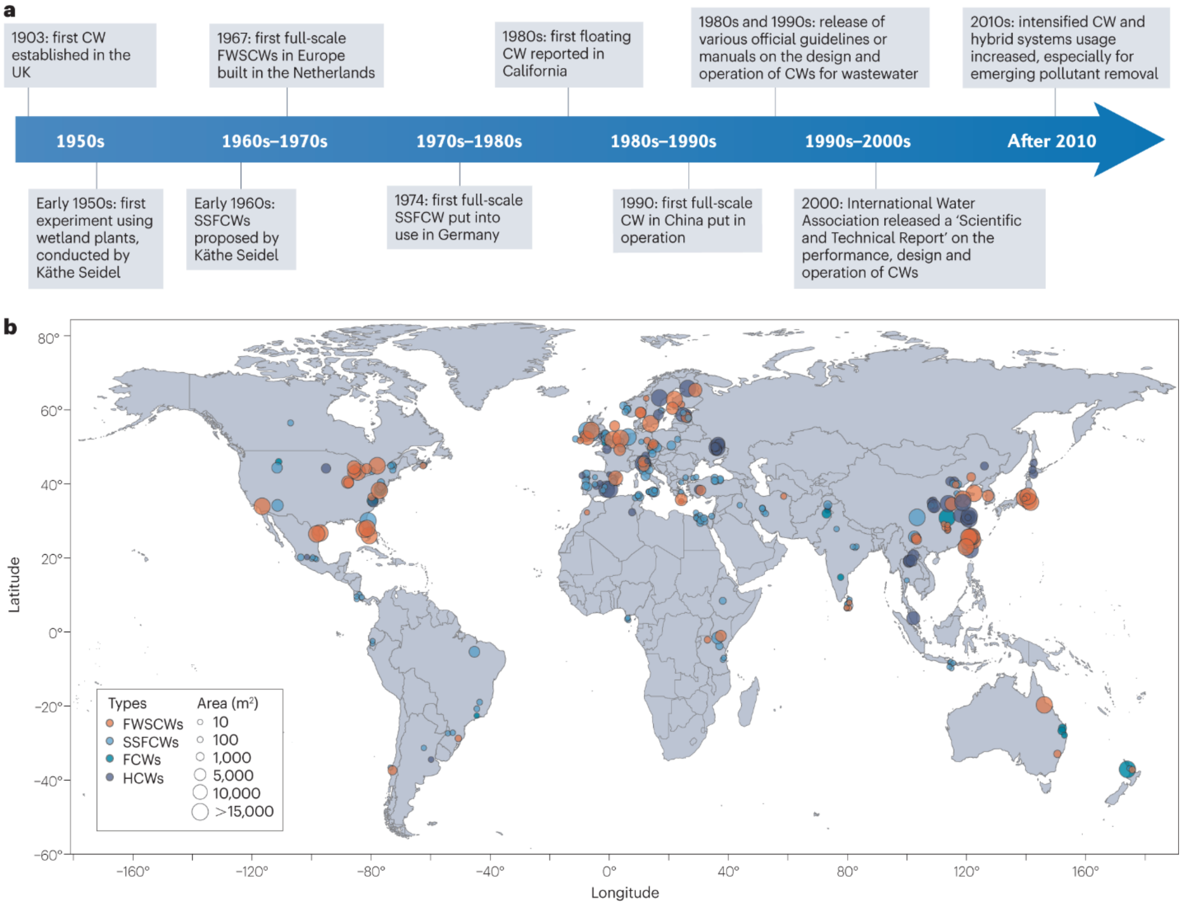

Figure 2.1: Map of global distribution of constructed wetlands

(Source: Adapted from Wu *et al.*, 2023)

2.3 Conceptual framework

For the constructed wetland that treats agro-industrial wastewater, the conceptual framework explains how wastewater inputs (BOD, COD, TSS) interact with wetland design features (hydrology, substrate, macrophytes) and treatment mechanisms (physical, chemical, and biological) to determine the quality of the effluent released to the environment. Additionally, it explains how constructed wetlands serve as an integrated ecological system that functions by removing organic materials and nutrients, degrading resistant compounds such as polyphenols, adsorbing, and precipitating suspended particles, among others.

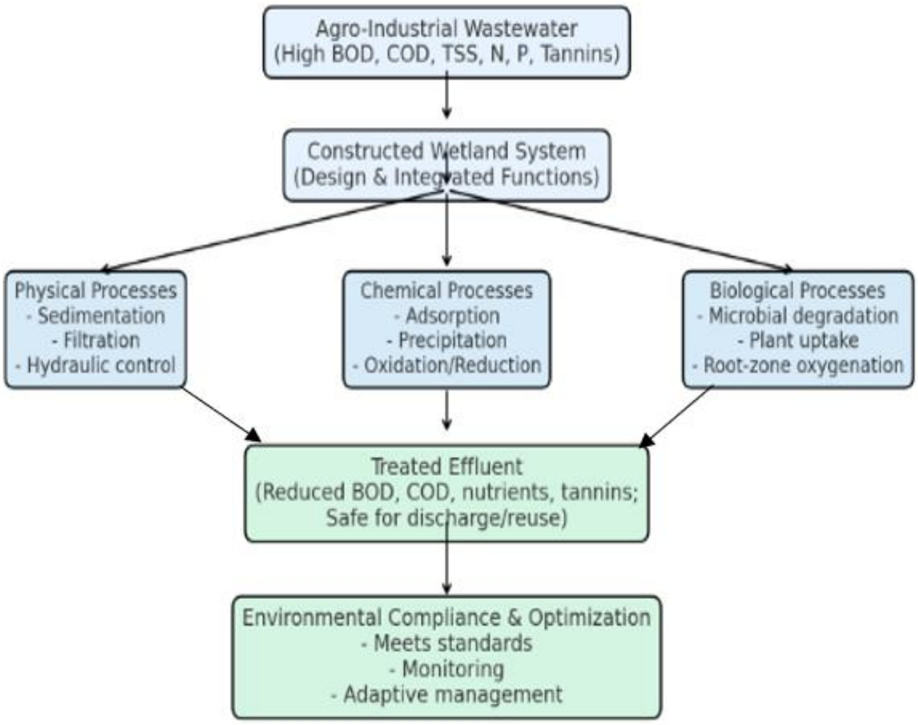

Figure 2.2: Conceptual framework of constructed wetland processes for agro-industrial wastewater

(Source: Adapted from Kadlec and Wallace, 2008)

2.4 Emerging trends in constructed wetlands

Recent advancements in constructed wetlands are aimed at increasing efficiency and long-term sustainability. Hybrid CWs, which include vertical and horizontal flow units, effectively treat agro-industrial wastewater (Wu *et al*., 2014). Nanomaterials, such as the use of biochar and nano iron, are being used to improve the adsorption of resistant pollutants, including tannins and heavy metals (Zhang *et al*., 2022). Additionally, machine learning methods now forecast constructed wetland performance under various loading and environmental conditions (Guo and Cui, 2022). On the other hand, automation and smart monitoring by use of sensors facilitate real-time control of all constructed wetland processes (Li *et al*., 2023). At the same time, climate change impacts such as droughts, floods, and temperature changes put strains on CWs, affecting microbial processes and treatment efficiency (Ricart & Rico-Amoros, 2021). Together, these advancements point to more adaptable, durable, and technologically advanced CW systems for long-term wastewater management.

2.5 Classification of constructed wetlands

This refers to the frameworks or criteria used to categorize the constructed wetlands based on the dominant plant growth forms (Vymazal, 2011). Therefore, the macrophyte-based classification of CWs can be free-floating, emergent, submergent, or multistage. Therefore, macrophytes are crucial in that they serve as habitats for animals, remove nutrients from the environment, filter suspended particles, and increase surface area for microbial attachment (Srivastava *et al.,* 2008).

2.5.1 Emergent macrophyte-based treatment system

Consists of emergent types of macrophytes in the constructed wetland, such as common reed (*Phragmites mauritianus*), cattails (*Typha spp*.), and *Cyperus papyrus,* among others, forming this type of treatment system, anchored to the substrate and allowing microbial colonization (Ijoma *et al*., 2024). Additionally, they increase the surface area for microbial attachment and quicken the nitrification process, thus removing nutrients from the environment, drawing oxygen from the air, and holding it in their roots, creating an oxidized rhizosphere (Armstrong, 1980). In that conjunction, regular harvesting of above-ground biomass is crucial for the treatment system operation to increase efficiency and prevent clogging based on studies of Manolaki *et al*. (2021), but seasonal changes and limited efficacy in the root system limit treatment effectiveness (Brainkart, 2003).

2.5.2 Submerged macrophyte-based treatment system

The treatment system uses submerged plants such as *Ceratophyllum demersum* and *Elodea canadensis* to absorb nutrients in water through shoots and leaves. Through photosynthesis, plants give out oxygen into the water and can also increase water clarity by lowering suspended particles in the water (Velthuis *et al*., 2017). Additionally, deeper water zones are home to the plants used in this treatment system. Despite their importance, their surface area is insufficient for microbial decomposition, leading to potential pollution and eutrophication (Mao *et al*., 2024). Han *et al.* (2018) and Manolaki *et al.* (2021) state that regular plant harvesting is crucial to prevent plant breakdown and nutrient release, as the main gap with this treatment system is its potential uprooting during intense winds.

2.5.3 Free-floating macrophyte-based treatment system

This constructed wetland consists of freely floating marsh vegetation like the water hyacinth (*Eichhornia crassipes)* and *Azolla spp.,* which are easily propelled by wind and water currents (Canadian Pond, 2024). They efficiently absorb nutrients from water, while only a small percentage supports microbial communities that break down pollutants (Zhang *et al.*, 2023). Additionally, these plants are flexible and easy to move and harvest without disturbing the substrate (Luhar and Nepf, 2011). The wetland plant type requires frequent harvests and shallow roots, requiring above-ground biomass control for effective pollution removal (Zhu *et al.*, 2022). To add, free-floating macrophytes may not effectively remove organic toxins and heavy metals (Kivaisi, 2001).

2.5.4 Multistage macrophyte-based treatment system

Technology effectively removes pollutants from wastewater using horizontal and vertical flow systems and macrophytes, removing nitrogen and ammonia (Kivaisi, 2001). It is versatile, energy-efficient, and environmentally beneficial (Kivaisi, 2001). However, it requires extensive acreage to operate, it is expensive, and the constructed wetland performs differently over different seasons and functions slowly due to frequent blockages (Stein and Hook, 2005). Additionally, regular monitoring is necessary to determine the optimal macrophyte for nutrient removal (Li *et al.*, 2024).

2.6 Types of constructed wetlands

This refers to grouping the constructed wetlands based on the design types, such as horizontal subsurface flow wetlands (Vymazal, 2007). Additionally, it can be based on the function or use of CW, such as storm water management, and even household use. Therefore, the types of constructed wetlands can be horizontal subsurface flow wetlands, free subsurface flow wetlands, among others.

2.6.1 Free water surface (FWS) flow /surface flow (SF)

These types of wetlands are shallow and can effectively treat wastewater through complex interactions between plants and liquid-phase biofilm (Kadlec and Wallace, 2008), allowing denitrification in the bottom layer that is sealed and nitrification and ammonification on the top parts (Kadlec & Wallace, 2008). Furthermore, FWS effectively removes pollution indicators like TSS, COD, and BOD through microbial degradation and filtration (Kadlec & Wallace, 2008), with nitrogen removal efficacy varying from 40-50% based on nitrogen compound type, temperature, dissolved oxygen level, and season (Vymazal, 2007). Additionally, its shallow water table removes 40-90% phosphorus, offering low operation costs, simpler technology, and low odour, but it has a weakness of requiring more area for operation (Agarry *et al.*, 2020).

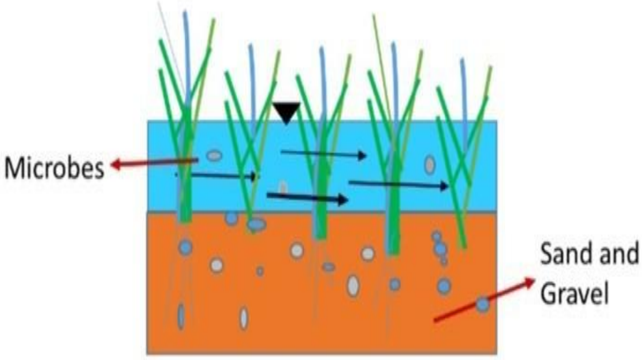

Figure 2.3: Schematic diagram showing surface flow system

(Source: Vymazal, 2011)

2.6.2 Subsurface flow system (SSF)

The system allows water to be below soil level and is sealed at the bottom, effectively removing solids from wastewater through grit removal and sedimentation methods (Smarzewska & Morawska, 2021). Additionally, subsurface flow systems are better than surface flow systems, including their ability to endure cold temperatures, can function well in small areas, have high sorption capacity, and to minimize odour. However, it demands more construction funds and is at risk of pore clogging (Langergraber, 2019). Therefore, SSF may be horizontal or vertical according to Hassan *et al*. (2021).

2.6.2.1 Horizontal subsurface flow system (HSSF)

This type of CW system is more popular than the VSSF-constructed wetlands in that it allows water to flow horizontally across a surface packed with specific gravel sizes and sand. To add, sedimentation tanks are also used to filter wastewater particles and prevent clogging in this wetland system (Langergraber, 2019). This system also uses emergent macrophytes to transport oxygen to the root rhizosphere for microorganism breakdown and metabolism (Langergraber, 2019). The method eliminates BOD_5 and COD in wastewater at a rate of 75% and 64%, respectively (Puigagut *et al.,* 2007).

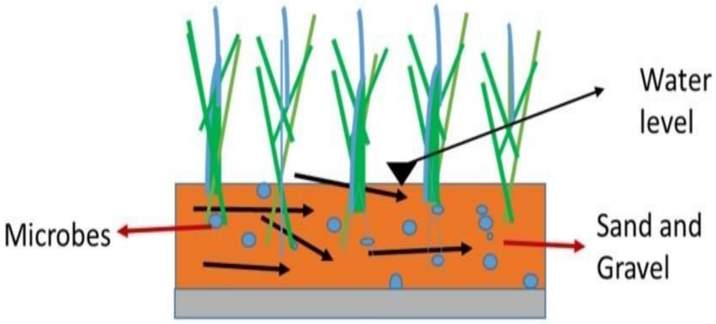

Figure 2.4: Schematic diagram showing horizontal subsurface flow
(Source: Vymazal, 2011)

2.6.2.2 Vertical subsurface flow system (VSSF)

In this system, water flows through a vertically positioned substrate using a pump or gravity through the filter beds. The system functionality is also determined by its residence time and the hydraulic loading rate (Langergraber, 2019). Additionally, the system contains more oxygen for bacterial development, the nitrification process, adsorption capacity, and filtration. This process occurs very efficiently in this system compared to the HSSF system (Hdidou *et al*., 2021). Despite its high maintenance and design cost, it has low capital cost, thus achieving high removal rates of pollution indicators such as BOD, COD, and TSS (Igwegbe *et al*., 2022).

2.7 Wastewater sources and characteristics

Wastewater refers to water that is negatively impacted by human activities, often containing a complex mixture of pollutants that alter its natural quality. Wastewater is classified into chemical, physical, and biological characteristics, varying significantly based on its source (Sigma Earth, 2022). The diversity and the concentration of these pollutants make wastewater an environmental concern since it affects the water quality and harms the aquatic ecosystem.

2.7.1 Physical characteristics and sources

Fresh wastewater, sourced from organic matter and garbage, is gray, black if dirty, and has a rotting stench due to gases like hydrogen sulfide (Sigma Earth, 2022). Furthermore, it may contain suspended and dissolved solids from domestic and industrial sources and has a higher temperature than ambient water (Sigma Earth, 2022).

2.7.2 Chemical characteristics and sources

Wastewater derived from organic chemicals such as carbohydrates, fats, oils, pesticides, and phenols is sourced from domestic, agricultural, industrial, and commercial wastes that contain nutrients like nitrogen and phosphorus, contributing to water quality issues (Sigma Earth, 2022). Additionally, it has a pH range of 6.5 to 8.5, according to the School of PE (2018), and may also contain heavy metals, alkalinity, chlorides, and chemical gases such as methane and oxygen (Sigma Earth, 2022).

2.7.3 Biological characteristics and sources

Wastewater can contain bacteria, viruses, fungi, and algae, posing health concerns to the public. Their sources might be from industrial wastewater and treatment plants (School of PE, 2018). When we know the biological characteristics and sources of this waste, we will highlight the need for nutrient removal in terms of macrophyte uptake. Understanding nitrogen removal in CWs through macrophyte uptake requires a thorough understanding of the physical, chemical, and biological properties of the wastewater. Additionally, it provides insight into monitoring parameters and assessing treatment effectiveness. Understanding these characteristics and sources helps assess pollutant reduction in constructed wetlands and provides a benchmark for monitoring in the field.

2.8 Physical, chemical, and biological composition of tea extract wastewater and its impacts

2.8.1 Biological oxygen demand (BOD)

It refers to the amount of oxygen that the microorganisms need to break down organic matter in water at 20°C for five days (dissolved oxygen) expressed in mg/L (YASA ET, 2023), with high BOD indicating increased concentrations of biodegradable organic matter, which may cause oxygen depletion in aquatic systems thus harming the aquatic life thus requiring adequate treatment to comply with environmental regulations. The typical range for BOD in tea extract wastewater is between 155 and 330mg/L, and it varies based on tea leaf quality, seasons, and the cleaning activities in the tea factory. Tannins, polyphenols, and tea compounds such as caffeine increase BOD levels, thus requiring compliance with environmental regulations (Avada Environmental, 2024). Therefore, there is a need for primary and secondary treatment processes to reduce BOD levels. Additionally, the use of aerators and constructed wetlands can help manage BOD levels in water (Vymazal, 2011).

2.8.2 Chemical oxygen demand (COD)

It is the amount of oxygen required to chemically oxidize both biodegradable and non-biodegradable organic compounds in water, expressed in mg/L (Metcalf and Eddy, 2003). It is a more accurate indicator of organic pollution levels than BOD (Avada Environmental, 2024). High COD levels in tannin and caffeine can degrade water quality and deplete oxygen levels; therefore, there is a need to ensure its compliance with environmental set standards. In that context, COD is utilized in wastewater management to determine treatment efficiency (Xu & Cui, 2019). Furthermore, the usual ranges of COD in tea extract wastewater are 300-900mg/L, which fluctuates depending on the organic load and the chemical cleaning agents used in the tea factory. Therefore, COD levels in the wastewater can be managed using advanced methods such as the activated sludge, improved oxidation techniques, and constructed wetlands.

2.8.3 Tannins

Naturally occurring polyphenol compounds found in the tea leaves contribute to their deep brown colour and occur because of the high organic load in wastewater (Hill, 2019). In the tea extract effluent, it typically varies between 50 and 150 mg/L; however, this varies depending on the tea variety and water used in the processing. In addition, bacteria can partially degrade tannins, increasing COD and BOD levels (Vijayaraj *et al.,* 2018). On the other hand, untreated tannins can lower the pH, interfering with wastewater treatment, reducing water transparency, and thus preventing photosynthesis. Therefore, microorganism biodegradation, the use of coagulants in the pretreatment process, and phytoremediation by macrophytes, which occurs primarily in the constructed wetlands, are examples of management strategies for reducing tannin in wastewater.

2.8.4 Total suspended solids (TSS)

This is the total amount of non-dissolved particles in wastewater, which can be organic materials, plant debris, silt, or clay (Bilotta & Brazier, 2008). TSS levels in tea extract effluent typically range between 100 and 300mg/L, and they vary depending on the factory cleaning operations and excess runoff after heavy rains. Excessive TSS concentrations can impact aquatic habitats, degrade water quality, limit the effectiveness of the wastewater treatment, and clog aeration and filter systems (Vymazal, 2007). As a result, management strategies for lowering TSS concentrations include sedimentation processes, filtration, the use of vegetated buffers, and constructed wetlands. Therefore, TSS is an essential measure of wastewater quality and, by extension, enhances the treatment process efficacy.

2.8.5 Nitrogen compounds

Tea wastewater contains organic nitrogen, ammonia, ammonium, nitrite, total nitrogen, and nitrate derived from the tea leaves and synthetic fertilizers, and is measured in mg/ L. The average range for nitrogen components in tea extract wastewater is TN (50-150mg/L), ammonium (20-85 mg/L), nitrate (5-30mg/L), and nitrite (0.01-1.5mg/L) according to Aide *et al.* (2020). Nitrogen compounds tend to fluctuate depending on the organic load in the wastewater and the amount of fertilizer used during the tea planting. Excess nitrogen molecules in water can cause eutrophication, harmful effects to aquatic life, and groundwater contamination. Furthermore, the breakdown of organic nitrogen produces ammonia, which, depending on the pH of wastewater, might be ammonia or ammonium (Khajal *et al.*, 2020). In addition, depending on the oxygen concentration, ammonium can produce nitrite and nitrate. Therefore, regulating nitrogen compounds in wastewater, denitrification, nitrification, plant uptake, and fertilizer use regulations on the tea farms can all help to reduce their concentrations in the water.

2.8.6 Phosphorus compounds

Phosphorus compounds in tea wastewater may include orthophosphates, polyphosphates, and organic compounds. Most phosphates in tea wastewater are orthophosphates. The normal range for total phosphorus in tea extract wastewater is 5 to 30mg/L, and it varies depending on the fertilizer used in tea cultivation as well as the cleaning agents used during tea processing. These compounds are generated during processing, and if wastewater is not treated, it can cause nutrient pollution, eutrophication, and poor water quality (Feng *et al.*, 2023). As a result, discharge limitations established by the government should be upheld. To manage phosphorus compounds in tea extract effluent, chemical precipitation, adsorption by sediments, filtration, and plant absorption in constructed wetlands can be useful strategies.

2.9 Pollutant removal mechanisms of a constructed wetland

It involves a combination of physical, biological, and chemical processes that work together to eliminate or minimize contaminants in a constructed wetland (Kadlec and Wallace, 2009). A sedimentation technique can physically remove all TSS, as well as when water seeps through the soil matrix and the root system of plants (Hassan *et al.*, 2021).

Sunlight, biodegradation, and adsorption are biological ways for removing tannin from wastewater, which reduces its content by attaching to organic molecules or soil particles in wetland environments. Furthermore, bacteria and fungi can break down tannins into simpler molecules, reducing their impact on water quality (Koopmann *et al.*, 2023).

Wetland bacteria tend to reduce COD levels by a chemical elimination process that breaks down organic matter into carbon dioxide and water. Additionally, anaerobic bacteria ferment and reduce COD levels in anaerobic zones, whereas aerobic bacteria oxidize it. When anaerobic bacteria degrade organic debris in wetlands, oxygen is used, and BOD levels drop. Macrophytes like *Phragmites sp* and *Typha sp* transport oxygen to their roots, promoting aerobic microbial activity (Ge *et al.*, 2017).

Wetland plants reduce nitrogen from water bodies by biological removal, lowering their concentration by producing other forms of nitrogen like ammonia (Aide *et al.,* 2020). Furthermore, through the process of nitrification, the Nitrosomonas bacteria convert ammonium (NH_4^+) to nitrite (NO_2^-), and the Nitrobacter transform nitrite (NO_2^-) to nitrate (NO_3^-), lowering their concentration in the environment (Aide *et al.*, 2020). Moreover, denitrifying bacteria convert nitrates to nitrites, which can be converted to nitrogen gas at elevated temperatures or in anaerobic zones without oxygen (Khajah *et al.*, 2023). Some ions can be adsorbed into soil particles, decreasing their water mobility, and ammonium (NH_4^+) can volatilize, escaping into the atmosphere as a gas in warm, high-pH environments (University of Hawai, 2007). Nitrogen is temporarily held in plants for growth and is removed when harvested.

Aquatic plants consume dissolved organic and inorganic phosphate to lower the water column concentration (Aide *et al.*, 2020). Phosphorus is adsorbed in soil particles, forming phosphates and precipitating as insoluble compounds of calcium, iron, and aluminum phosphate (Aide *et al.*, 2020). Additionally, particulate phosphorus detaches from the water column and settles in the sediment. Furthermore, some microbes can assimilate phosphorus through metabolism and reproduction, immobilizing it and incorporating it into their microbial biomass (Shirdashtzadeh *et al.*, 2022).

2.10 The role of the algal pond in wastewater treatment

An algal pond, an affordable open-water source, enhances the treatment process by utilizing sunlight for photosynthesis and microalgae for aerobic bacteria, and thus the aerobic state of the pond improves the treatment process (Linden, 2013). Algae-based systems effectively absorb nitrogen and phosphorus, making them suitable for wastewater treatment through assimilation, nitrification, and denitrification (Fallahi *et al.*, 2021). Before being incorporated into algal biomass, algae use nitrogen as ammonium and nitrate for protein synthesis, while heterotrophic bacteria in anaerobic zones and algal biofilm aid in denitrification (Beardall & Raven, 2020).

Algae effectively remove phosphorus from wastewater through ion exchange and adsorption processes (Ugwuanyi *et al.*, 2024) and absorb nutrients through biological assimilation and precipitation in algal ponds (Narvarte *et al.*, 2023). Furthermore, algal biomass can be utilized for animal feed, fertilizer, and biofuels, and algal ponds offer sustainable wastewater management by processing and producing useful products (Ugwuanyi *et al.*, 2024).

Open pond treatment systems are susceptible to a variety of environmental and biological stresses, which reduce algal productivity and nutrient removal effectiveness. Uncontrolled influxes of contaminants, common grazers, and intense evaporation can rupture cell membranes and induce population collapse (Bhatt *et al.*, 2022). Furthermore, in areas with high sun irradiation and low humidity, intense evaporation concentrates dissolved salts and nutrients, changing the community composition toward less efficient species. Additionally, temperature fluctuations and storms can cause thermal or light-stress reactions, decreasing metabolic activity and nutrition intake. To maintain stable, high-density algal cultures, close monitoring and adaptive management are necessary (Bhatt *et al.*, 2022).

2.11 Nutrient removal by macrophytes in constructed wetlands

Macrophytes are essential components of constructed wetlands, having an important function in nutrient removal, particularly phosphorus (P) and nitrogen (N). Additionally, these plants directly absorb nutrients, enhancing microbial transformations and physically stabilizing sediments. Also, some emerging macrophytes, such as *Phragmites australis* and *Cyperus papyrus,* are used frequently because of their high biomass output and broad root systems, which promote sedimentation and offer aerobic zones in the rhizosphere that aid in nitrification (Vymazal, 2007).

Nitrogen is eliminated by microbial mechanisms such as nitrification, denitrification, and ammonification, which are aided by the transfer of oxygen from the atmosphere to the plant roots and the availability of carbon substrates in root exudates (Tanner, 2001). On the other hand, phosphorus removal occurs when the root system of the macrophytes captures sediments that can bind phosphorus, which is adsorbed by calcium (Ca), iron (Fe), or aluminum (Al) (Kadlec & Wallace, 2008). Additionally, precipitation can also remove phosphorus from the environment. Furthermore, nutrients build up in above- and below-ground biomass, which can be eliminated by routine harvesting (Akratos & Tsihrintzis, 2007).

Despite these well-known benefits, there are significant research gaps in understanding the specific mechanisms and efficiency of nutrient uptake by various macrophyte species under diverse environmental and operating situations. Much research offers broad performance indicators for constructed wetlands without distinguishing between the individual contributions of plant species and microbial populations. For example, it is uncertain how much nitrogen is eliminated through direct plant uptake versus microbial mediated mechanisms, particularly in systems with varying loading rates or climates (Brix, 1997).

Furthermore, long-term data on phosphorus retention are scarce, particularly addressing substrate media saturation and the significance of various harvesting procedures in limiting phosphorus release back to water (Vymazal, 2007). Additionally, there is a scarcity of region-specific studies that assess native or regionally adapted macrophytes, which may provide better nutrient removal performance or greater resistance under local environmental conditions (Tanner, 2001). Future research should consider quantifying species-specific uptake rates, investigating the synergistic impacts of macrophytes and microbial consortia, and assessing sustainable management practices, including rotational harvesting and integrated wetland-polishing systems.

2.12 Factors influencing the performance of constructed wetlands in treating tea extract wastewater

The efficiency of a constructed wetland in treating tea extract wastewater depends on several interrelated factors, including biotic, abiotic, and environmental conditions. One of the most important aspects is the choice of plant species or macrophytes. Macrophytes have a substantial impact on wetland performance because they improve nutrient uptake, promote root rhizosphere oxygenation, and aid in the decomposition of organic wastes via root exudates and microbial decomposition (Brix, 1994). Similarly, the type of substrate used in CWs, such as sand and gravel, affects treatment system effectiveness (Brix, 1994). On the other hand, the substrate has a wide surface area for microbial biofilm growth, which aids in filtration and adsorption of organic pollutants, enhancing CWs' efficacy (Vymazal, 2011).

Temperature has a direct impact on microbial activity and metabolic reactions in wetland ecosystems. When the temperature is warm, the rate of organic matter breakdown increases, boosting nitrogen cycling, while when the temperature is cold, microbial processes slow down, lowering treatment efficiency (Kadlec and Wallace,2008). On the other hand, dissolved oxygen (DO) levels are crucial, particularly in subsurface flow wetlands. When the DO level is high, aerobic microbial activity occurs, necessary for nitrification of both ammonium and nitrite, resulting in the breakdown of organic contaminants in wastewater (Vymazal, 2007).

The composition and quality of the influent entering the constructed wetland affect its treatment efficiency. When the pollutant load exceeds the constructed wetland treatment capacity, the pollutant retention time in the wetland should be increased, or wastewater needs to be pre-treated before entering the constructed wetland for effective pollutant removal (Mburu *et al*., 2013). Furthermore, the structure and diversity of a wetland's microbial community are critical for long-term pollutant elimination. Therefore, microorganisms tend to decompose organic matter, enhancing nutrient cycling and therefore helping in eliminating pathogens (Zhang *et al.*, 2023).

Temporal and seasonal changes have an additional impact on the CW performance. Seasonal variations in temperature, precipitation, and sunlight have an impact on plant growth, microbial activity, and the hydraulic loading rate (Benbouzid *et al*., 2024). During warmer months, plant growth and microbial metabolism both increases, improving nutrient removal and organic matter breakdown. Excess rainfall, on the other hand, may dilute the influent concentrations and hence reduce the hydraulic retention time, lowering the treatment efficiency (Benbouzid *et al*., 2024). Additionally, emergent macrophytes grow rapidly during the wet season, enhancing their ability to absorb nutrients (Li *et al*., 2024). Therefore, these considerations taken together highlight the complexity of CW systems, as well as the need for site-specific designs and management to improve on tea extract waste management.

2.13 Operation and maintenance of wetlands

This entails planning, monitoring, and general management tasks that contribute to the functions intended during the design of the constructed wetland. Therefore, Auckland Council (2020) emphasized the importance of maintaining CWs by cleaning the inlets, inspecting the blockages, controlling the weeds, and conducting regular inspections of both the invasive and native species. Mechanical and manual removal methods such as use of hand pulling are effective ways of operating and maintaining the wetlands (Queensland, 2024). Additionally, water levels should be adjusted to avoid weed growth, and frequent inspection and weed treatment are required to maintain a healthy wetland ecology (UN-HABITAT, 2008). Furthermore, regular checks on the solid and organic matter content are required for the pretreatment unit operation and maintenance. In addition, the inspection of the wetland structure, embankments, and slope is necessary to prevent blockages (Aide *et al*., 2020). Water quality in wetlands varies throughout time, necessitating monitoring and laboratory examination on a regular basis. On the other hand, effective mosquito management, such as variation of the depths of the CWs, vegetation growth management, and preventing ponding in subsurface flows, can reduce mosquito breeding and improve water quality in constructed wetlands (Queensland, 2024).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study area

Finlays Saosa constructed wetland was the study area, located within latitude 0.245 °S & 0.251 °S and longitude 35.186°E & 35.19 °E near the Finlays Tea Extracts (Kenya) Limited (FTEK) in Kericho county in Kenya (Figure 3.1). Finlays treatment plant is associated with James Finlays Tea and Flower factory, where it receives and treats tea wastewater from the factory and the surrounding tea farms, and releases partially treated wastewater to Finlays Saosa constructed wetland for further treatment. Additionally, FTEK treats massive quantities of tea extract wastewater per day, around 300,000 litres (Finlays, 2020). Established in Scotland in the 18th century, the company expanded into Kenya's tea industry in the early 20th century (Finlays, 2020). Recognized internationally for producing black, green, and instant tea, the estate covers a large area with tea plantations, forested areas, and catchment areas for irrigation and local biodiversity (Finlays, 2020).

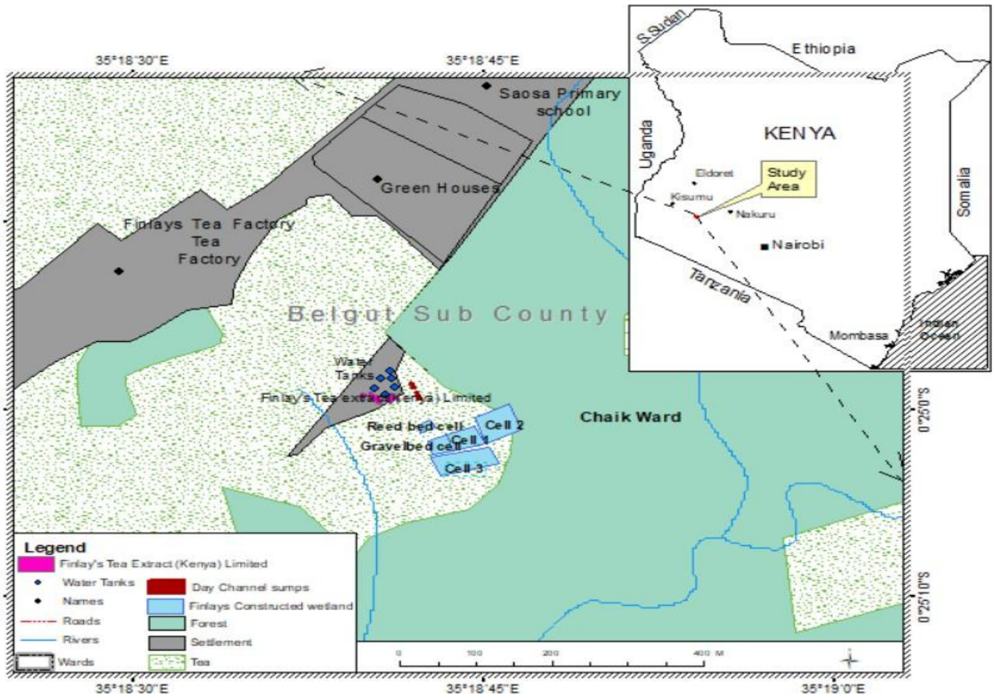

Figure 3.1: Map of Finlays Saosa area showing location of constructed wetland

(Source: Survey of Kenya, 2024)

3.1.1 Study site description

During the research, there were 7 sampling points in the study area in the Finlays Saosa-constructed wetland along the wastewater treatment pathway, covering a total area of about

4228. 58m^2. The cells were interconnected such that the outlet of a cell served as the inlet to the next cell in the sequence. Raw wastewater from Finlays factory entered the day channel sump and flowed to the conventional treatment plant before being directed to the clarifier that served as the first sampling point. The reed bed cell, a free water surface flow type of constructed wetland, was the first cell to have an inlet section to the constructed wetland, receiving wastewater by gravity from Finlays Saosa treatment plant, and functioned as the second sampling point. It has a depth of about 80 cm and was covered by reeds that tend to dry out during the dry season. Additionally, the cell featured mesh blocks for restraining floatables from flowing to the gravel bed. Additionally, the reed bed cell had an outlet, which functioned as the third sampling point during the research work.

The gravel-bed cell was a horizontal subsurface flow wetland with few plants. It received water from the reed bed cell's outlet via a pipe, and its outlet served as the fourth sampling point. Cell 1, located next to the gravel bed cell, was a free water surface flow wetland and an algal pond featuring distinct types of macrophytes along its sides, which aid in nutrient removal. Additionally, it had an outlet that served as the fifth sampling point during the research.

Cell 1 is linked to Cell 2, which is also a free water surface flow wetland and algal pond. Together, the two cells support algae that promote photosynthesis, and release oxygen gas that microbes use to break down organic matter. The outlet of Cell 2 was the sixth sampling point during the field work. Cell 3 was the final cell that completed the wastewater treatment process, receiving water from Cell 2 through pipes, discharging its water to the soak pit, and then to the river, and its outlet served as the seventh sampling point. The wetland contains a variety of macrophyte plants such as *Cyperus papyrus, Phragmites australis, Elodea canadensis, Typha latifolia, and Colocasia esculenta,* among others. Finlays Saosa- constructed wetland is a multi-stage macrophyte-based treatment method, as all the various cells work together, as shown in Figure 3.2 and Plate 3.1.

Finlays Saosa constructed wetland had 5 cells that varied in length, width, and depth as shown in Table 3.1, with Cell 2 being the largest with a surface area of about 1522 m^2, and the reed bed cell being the smallest with a surface area of about 237.6 m^2. Cell 1 has a higher volume of water of about 1051 m^{3,} but it varies with the season, with the gravel bed having a low volume of water on the surface of about 64.30 m^3. Despite Cell 2 having a high surface area, it has the lowest depth of 0.29m, and the day channel has a high depth with a lower surface area.

Table 3.1: Technical description of Finlay Saosa constructed wetland

Parameter	**Description**
Location	Finlays Tea extracts (Kenya) Limited (FTEK), in Saosa, Kericho county, Kenya
Start date of operation	2014 to date
CW type	Free waster surface flow(FWS), Horizontal Subsurface Flow (HSSF)
CW configuration	FWS Reedbed cell, FWS Cell 1-3, HSSF Gravel bed cell
CW substrate	Gravel, sand
Type of wastewater	Tea extract wastewater
Wastewater flow per day	300 m^3/day (300,000 litres)-To the treatment plant
Pretreatment	Finlay Saosa treatment plant
Types of feeding	Wastewater from the factory is sent to the treatment plant, and later, it continuously flows through the cells using pipes
Total surface area of the CW	4229.38m^2
Plant species	*Pontederia cordata, Colocasia esculenta, Cyperus papyrus, Phragmites mauritianus, Typha latifolia, Canna indica*
Constructed wetland sections	
Day channel sump	2.6m x 2m x 3m= Area: 5.2m^2, Volume:15.6m^3
Reed bed Cell	22m x 10.8m x 0.82m=Area: 237.6m^2 , Volume:194.83m^3
Gravel bed cell	21.9m x 22.6m x 0.13m=Area:494.94m^2, Volume:64.34m^3
Cell 1	35.8m x 22.6m x 1.3m=Area:809.08m^2,Volume:1051.8m^3
Cell 2	41.6m x 36.6m x 0.29m=Area:1522.56m^2,Volume441.54m^3
Cell 3	58m x 20m x 0.6m=Area:1160m^2 , Volume: 696m^3

(Source: UN-HABITAT, 2008)

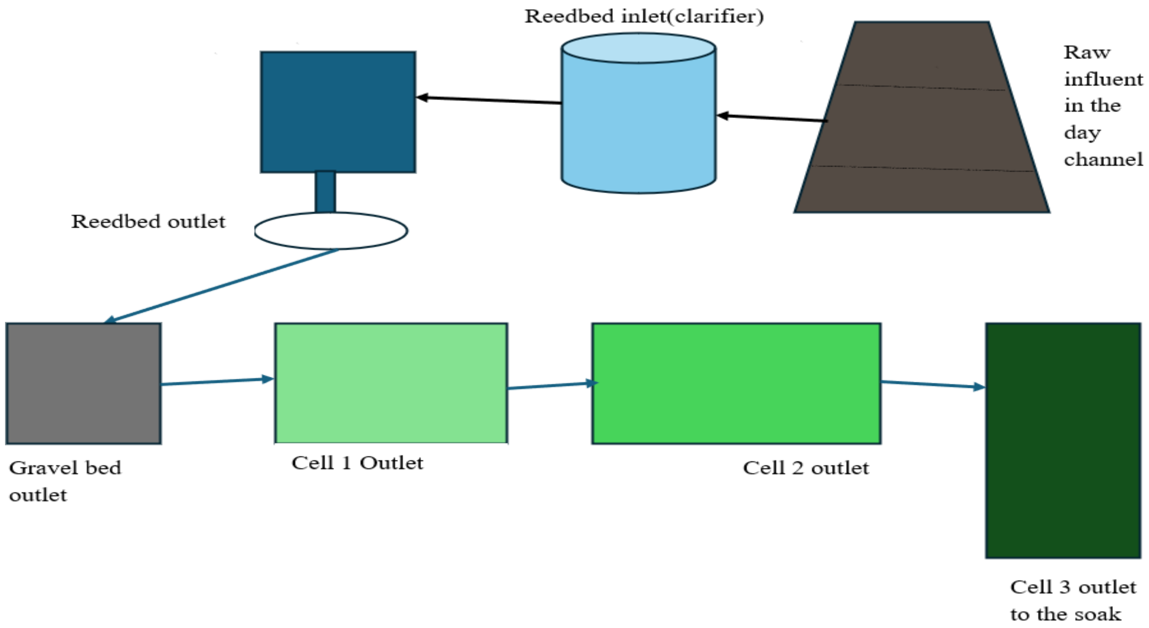

Figure 3.2: Schematic diagram of the sampling points in Finlays Saosa constructed wetland (The arrow shows the direction of flow of wastewater from the raw influent to Cell 3 outlet)

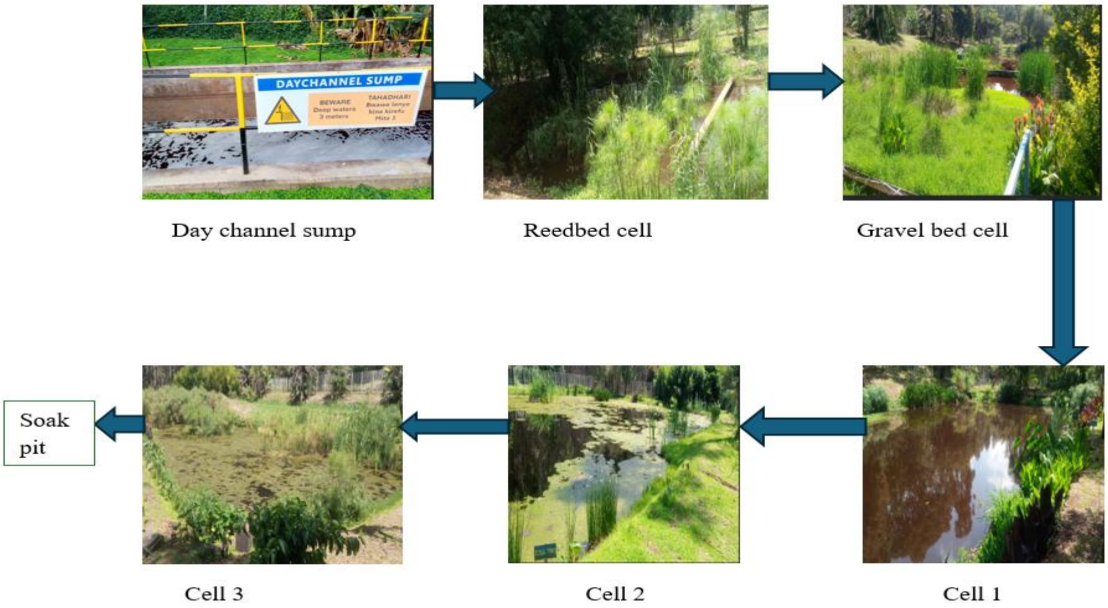

Plate 3.1: Photo showing the sampling sites arranged based on how the cells are connected along the wastewater treatment pathway

3.1.2 Climate of the study site

Finlays Saosa CW is located near the equator. The area experiences a tropical highland climate, characterized by temperatures ranging from 10°C to 25°C, with cold nights resulting from high altitude. It experiences rainfall twice a year, with long rains from May and June and short rains from September and November, and the yearly rainfall ranges between 1200 to 1500 mm (Mogaka *et al*., 2005). Additionally, high humidity promotes wetland vegetation, essential for wastewater processing, and affects water retention, flow rates, and efficiency of the constructed wetland (Mogaka *et al*., 2005).

3.1.3 Topography and geology

The Kericho highlands in Kenya are perfect for tea cultivation due to their mountainous terrain, easy water drainage, and gravity-fed wastewater treatment systems (Wulansari *et al*., 2022). Furthermore, the chilly, moist temperature, which ranges from 1800 to 3000 meters above sea level, has an impact on how the wetland functions (Mogaka *et al*., 2005). Additionally, the area is dominated by volcanic soils with high porosity and permeability, which allow for easy water percolation and wastewater treatment while still being extremely productive for tea development (Gachene *et al*., 2003). The clay soil in the area may store water for a lengthy period and be utilized for wastewater treatment and tea cultivation (UN-HABITAT, 2008).

3.2 Research design

A field-based quantitative experimental research design was used to collect, measure, and analyze data on nutrient concentration and plant biomass. On the other hand, treatment efficiency was achieved by using a quasi-experimental and observational approach, which involved evaluating the treatment efficiency before and after treatment without manipulating variables over space. During the research, there was limited replication of treatment cells due to single-season sampling. Field measurements involved the use of a calibrated multimeter model HQ 40D (HACH) to measure parameters in situ, including dissolved oxygen in mg/L, pH (on the pH scale), water temperature in °C, and electric conductivity in µs/cm, in each cell of the wetland. This measure was conducted whenever water samples were collected. Additionally, a graduated dipstick measured the water depth in each cell, and the surface area of every cell in the constructed wetland was measured using a measuring tape. Weather data was obtained from the Automated Rainfall and Data (ARD) weather station in Finlays to track the macrophytes' functioning.

3.2.1 Water samples collection and analysis

Five hundred (500) mL plastic bottles were used during the sampling to collect water samples, and they were washed and rinsed three times with the sample water before it was collected. The water samples were collected in triplicate per sampling point to evaluate physical, chemical, and nutrient parameters along the wastewater treatment pathway. Gloves were worn for safety purposes, and the sampled water was collected twice a month from each site from November 2024 to March 2025 and transported to the LWM laboratory Biological Science department for analysis. Furthermore, 14 water samples were collected per sampling session, labeled, and stored in ice-cool boxes. Whatman glass-fiber filters (0.45 µm, GF/C) filtered water samples for the test of ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), tannin, and soluble reactive phosphorus (SRP), all expressed in mg/L. Additionally, the Genesys 10 UV scanning spectrophotometer was used to measure the absorbance in nm (Plate 3.2). Unanalyzed water samples were placed in a refrigerator and analyzed the next day.

Plate 3.2: A spectrophotometer used to measure the absorbance

3.2.2 Plant sample collection and analysis

Macrophyte samples for the above-ground biomass were obtained in triplicate in the sampling sites, placed in carrier bags, and labeled for dry weight determination and nutrient removal. Additionally, the sample and sub-sample weights were obtained using a beam balance, placed in khaki bags. The samples were later dried in an oven at 70°C for a week for dry-biomass and ash-free dry weight determination, in g/m^2.

3.2.3 Biological oxygen demand $(BOD)_5$ determination in water samples

The study used Winkler flasks (250-300 ml), aluminum foil, an alarm clock oxygen electrode, and Winkler reagent for oxygen determination. Water samples were filled into dark flasks from the inlets and outlets of the cells, avoiding air bubbles and re-aeration, and oxygen concentration was measured after 5 days. The flasks were stored at 20°C according to the desired BOD formula (APHA, 2017).

$$\mathrm{BOD\ (mg/L)} = [(\mathrm{OE} - \mathrm{OS}) * \mathrm{F}] - \mathrm{D} \qquad (1)$$

O_S = Oxygen start concentration in mg/L, O_E = Oxygen end concentration in mg/L, F = Volume of the BOD bottles (mL/Volume of the sample water, D = BOD of dilution water in (mg/L).

The procedure above was utilized to determine BOD in water samples, measured in mg/L.

3.2.4 Chemical oxygen demand (COD) determination in water samples

The closed reflux colorimetric method, as described by APHA(2017), was used to measure COD by boiling a mixture of chromic and sulfuric acids to oxidize organic matter. A COD standard curve was created, and a mixture of digestion solution of H_2SO_4/ Ag_2SO_4, as well as stock Potassium Hydrogen Phthalate ($KHC_8H_4O_4$), was prepared. The digestion tube was initially filled with 2.5 mL of unfiltered samples, followed by 1.5 mL of digestion solution (Plate 3.3). An acid layer formed when 3.5 mL of $H_2SO_4/AgSO_4$ flowed downwards into the tube, covering the digestion solution sample layer. After the lid was tightened and the tube swirled for a few times to fully mix, everything was heated to 150°C in a preheating block for two hours, cooled, and the solution mixed and settled for analysis on the following day. Further, the supernatant was placed in 1 cm cuvettes, whereby the absorbance was measured against the blanks at 600nm wavelength.

Plate 3.3: COD samples analysis equipment set up at the LWM laboratory at Egerton University

The Biodegradability index (B.1) is a measure of the biodegradation potential in wastewater, used to determine the correlation between BOD to COD levels (Metcalf and Eddy, 2003). It was used to compute BOD to COD levels at each cell's inlet and outlet in a constructed wetland. This approach was also used to assess COD in water samples in mg/L.

3.2.5 Phosphorus compounds determination in water samples

The ascorbic acid technique (APHA, 2004) was used to assess the SRP in filtered water samples. The reagents were produced and combined in a ratio: A:B:C:D = 2:5:2:1; ammonium molybdate (A), sulphuric acid (B), ascorbic acid (C), and potassium antimony tartrate solutions (D), in that sequence. Following that, filtered water samples of 25 mL were mixed with 2.5 mL of combined reagents. After 15 minutes, absorbance was measured at 885nm against the blank. On the other hand, total phosphorus was formed by first breaking and reducing phosphorus in the unfiltered water samples to SRP using persulfate digestion. 25 mL of potassium persulphate was added to the unfiltered water samples, and the combination was autoclaved for 90 minutes at a temperature of 120°C (APHA, 2017). The above-indicated procedure was used for the determination of phosphorus compounds in water samples, and concentrations were expressed in mg/L.

3.2.6 Nitrogen compounds determination in water samples

Twenty-five (25) mL of filtered water samples was combined with 2.5 mL of sodium salicylate solution, and 2,5 mL of hypochlorite solution to measure ammonium (APHA, 2017). After that, the sample was incubated for ninety minutes in the dark at 25ºC. Thereafter, the absorbance was measured at 665 nm. Nitrate was also measured using the sodium-salicylate method, which entailed mixing 20 mL of the filtered water samples with 1 mL of newly prepared sodium salicylate solution (APHA, 2017). The sample was dried at 95ºC. After that, 40 mL of the distilled water was again added after the 1 mL of H_2SO_4 had been used to dissolve the residue. The absorbance at 420 nm was measured after adding 7 mL of the potassium-sodium tartarate solution. The sulfanilamide method (APHA, 2017) analyzed nitrite (NO_2^-) using reagents of sulfanilamide and N-naphthyl (1) - ethylenediamine-dihydrochloride solutions. 1 mL of sulfanilamide was added, followed by N- N-naphthyl (1)-ethylenediamine- dihydrochloride solution. After 2 to 8 minutes, 25 mL of filtered samples were measured at an absorbance of 543nm. In addition, TN was determined using the persulphate digestion method, whereby there was addition of 1 mL of the warm potassium persulphate to 25 mL of the unfiltered water samples to transform the nitrogen form into nitrate (APHA, 2017). Next, the sample was autoclaved for 90 minutes at 120ºC and 1.2 atm. The sodium-salicylate method assessed the total reduced forms into nitrate following digestion. The procedure was used for the determination of nitrogen compounds expressed in mg/L.

3.2.7 Total suspended solids determination in the water samples

Gravimetric measurement of TSS was performed on glass-fiber filters (Whatman GF/C) following drying to a constant weight at 95ºC. Pre-weighed Whatman GF/C filters with a particle size of 47 mm were used to filter a known volume of water samples. The samples were dried for three hours. The TSS was calculated with the formula (APHA, 2017).

$$\mathrm{TSS(mg/L)} = (\mathrm{Wc} - \mathrm{Wf}) \times 10^6)\, V^{-1} \qquad (2)$$

TSS=Total Suspended Solids, W_f=Weight of the pre-combusted filter in grams, W_c=Constant weight of the filter residue in grams, V=Volume of the water samples used in mL

The inorganic content of the water was determined by burning TSS filter papers for two hours at 500 degrees Celsius in a furnace. The organic content was calculated as TSS- (ash-free dry weight (AFDW). The above procedure of a gravimetric method was used to determine TSS and expressed in mg/L.

3.2.8 Determination of tannins in water samples

For tannin determination, 10 mL of tannin acid was dissolved in 1 litre of water, and during the process, a fresh solution was prepared for each determination. (1 mL = 0.5 mg of tannin acid). Thereafter, 0 to 10 mL of the aliquots of the standard tannin solution was pipetted into 100 mL of the volumetric flask containing 75 mL of water. 0.5 mL of Folin-Denis reagent, together with 1 mL of the 15% Na_2CO_3 solution, was added to each volumetric flask and made up to 10 mL with distilled water. Thereafter, a thorough mixing was done, and the tubes containing the reagents were incubated at room temperature for 20 minutes, and a bluish green colour was formed. The absorbance of the tannin was read at 700nm using the UV spectrophotometer. Tannin amount in the sample was calculated from the standard curve, using the above procedure, and the results were expressed as mg tannin acid equivalent/g (Rashmy Nair *et al.*, 2015).

3.2.9 Determination of the above-ground biomass of the different macrophytes in the constructed wetland and their nutrient removal capacities

Macrophytes were sampled once in January 2025 using a 0.5 x 0.5 square metre quadrant. During the collection, three replicate samples were taken for each dominant species in the cells found in Finlay's Saosa-constructed wetland. The macrophyte samples and subsamples were placed in carrier bags, weighed by a beam balance, and taken to the LWM Egerton University laboratory to be dried in the oven at 70ºC for a week. This was later used for the calculation of the above-ground biomass, and the dry weight was expressed in g/m^2. As stated by Okalebo *et al.* (2002), when using the acid digestion method, the proportion of total nitrogen and phosphorus in the weight of the ground-dried samples was analyzed to estimate the nutrient allocation in the above-ground biomass for each of the macrophytes (Okalebo *et al.,* 2002). A Universal Hammer Mill 9 FC- 22A was used to grind the oven-dried samples into a powder (Okalebo *et al.,* 2002). To determine the total nitrogen, 0.3 grams of the ground sample was digested and combined with 4 mL of the digestion mixture, made of concentrated H_2SO_4 with the selenium powder (APHA, 2017). In addition, a digestion block was used for the sample digestion for two hours at 110ºC and 330ºC, following the acid digestion method. The digested samples were cooled and transferred to a 100 mL volumetric flask, where they were diluted with distilled water. After adding 25 mL of the diluted sample to the digestion tube, 25 mL of the 40 mL NaOH solution was dispensed and fixed in the Kjeldahl distillation unit, as shown in Plate 3.4 (APHA, 2017). The samples were steam distilled by placing the conical flask at the receiving end of the distillation unit and adding boric acid together with 2 drops of the mixed indicator (methyl red and bromocresol green diluted in ethanol). 150 mL of the green distillate was backtitrated with 0.1M HCL, and the colour gradually changed from green to pinkish to grey.

Plate 3.4: Kjeldahl distillation unit used for Total Nitrogen determination in macrophytes

According to Okalebo *et al*. (2002), the percentage of Nitrogen (N) was computed using the titration volume as follows:

$$\mathrm{N}(\%) = (\mathrm{Ts} - \mathrm{Tb}) \times \mathrm{HCL\ molarity} \times \mathrm{Eq.wt\ of\ N} \times \mathrm{DF} \times 100\ \mathrm{w} \times 1000 \qquad (3)$$

Ts = Titer of the sample, Tb = Titer of the blank, Eq. wt of the N= 14.007mg, DF =Dilution factor DF = Dilution Factor, w =weight of the dried sample

N% obtained was used to calculate the accumulation of Nitrogen (N) per square metre biomass as stated by Okalebo *et al* (2002).

$$\mathrm{N}(\mathrm{g\ m} - 2) = \mathrm{N}\% \times \mathrm{Species\ biomass}\ (gm^{-2}) \qquad (4)$$

For the phosphorus analysis, the colorimetric method was used, whereby Ascorbic acid, sulphuric acid, ammonium molybdate solution, and molybdate reagents were prepared and mixed according to the required ratio, same as that of phosphorus analysis in water samples (Okalebo *et al*., 2002). A standard calibration curve was produced using standard procedures to ascertain the sample's concentration. (APHA, 2017). Four millilitres of the ascorbic acid solution, followed by three millilitres of molybdate reagent, and one millilitre of the digested sample in that order, were placed in a test tube and thoroughly mixed. For the colour to properly develop, the mixture was left to stand for an hour. The spectrophotometer read the absorbance at 880nm, and the phosphorus accumulation in grams per square metre was obtained using the formula below;

$$\mathrm{P}\ (\mathrm{g\ m}-2) = \text{Species biomass}\ (gm^{-2}) \times\ \ \mathrm{p}(mg)/(1000g \times 1000) \qquad (5)$$

Both Phosphorus and Nitrogen accumulation in macrophytes were expressed in g/m^2.

3.2.10 Determination of wastewater treatment efficiency

Finlays Saosa constructed wetlands' overall efficiency in treating tea extract wastewater was

obtained by comparing the mean loadings of the inlets and those of the outlets.

$$\%\ \text{efficiency} = \frac{\text{Inflow mean loading}-\text{outflow mean loading}}{Inflow\ mean\ loading} \times 100 \qquad (6)$$

3.3 Statistical data analysis

The information gathered from the field and the lab was kept in Microsoft Office Excel 2007. The data collected was statistically analyzed using IBM SPSS software version 28. Additionally, all tests were run at the significant threshold of $p<0.05$. Before the parametric testing, normality of data was checked using the Shapiro test, while the homogeneity of variance was determined using the Levene Test. All data about the physical parameters were normally distributed, except for nutrients and chemical parameters, which were not normally distributed. Therefore, data transformation was done using log base 10 to normalize the data. Thereafter, a parametric test was done to normally distribute the data. ANOVA found statistical differences existing in the physical, chemical, and nutrient parameters, except for DO, which showed no significant difference ($p> 0.05$). Additionally, the Tukey HSD post hoc test differentiated between the groups of means across the sampling location. A t-test compared the means of loadings and concentrations in the inlet and the outlet of the constructed wetland. On the other hand, descriptive statistics were used to present data about the physical, chemical, nutrient parameters, above-ground biomass, nutrient removal, vegetation cover, and removal efficiency of the constructed wetland. The results were presented using tables, bar graphs, and line graphs using descriptive statistics.

CHAPTER FOUR

RESULTS

4.1 Spatial variation in physical, chemical, and nutrient parameters along the wastewater treatment pathway

4.1.1 Weather characteristics in the study area

The weather data from December 2023 to March 2025 were used to explain temporal trends and fluctuations in physical, chemical, and nutrient parameters along the wastewater treatment system (Figure 4.1). The secondary data about the rainfall trends recorded at the Automated Rainfall and Data (ARD) weather station in Finlays Saosa had the potential to impact the constructed wetland's performance during the research period. The y-axis represented the rainfall data in mm, while the x-axis represented the months when the rainfall was analyzed. Additionally, the average annual rainfall between 2023 to 2025 was 201.94 mm, indicating a consistently elevated level of precipitation in the region. Additionally, the highest monthly rainfall occurred in April 2024, 381mm, while the lowest was observed in January 2025, a total of 63mm. Monthly rainfall during the study period ranged between 62 mm and 272.9 mm, with January 2025 recording the minimum monthly rainfall and March 2025 recording the maximum monthly rainfall. These pattern bars in Figure 4.1 suggest potential variation in the hydraulic loading rate and water retention capacity in the CW. Such variations are critical in assessing seasonal impacts on pollutant removal efficiency and vegetation performance.

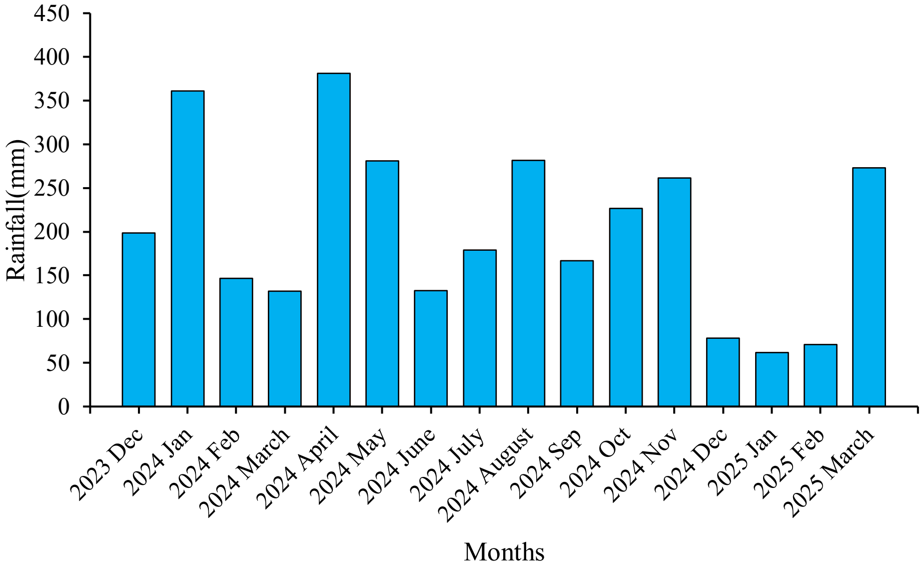

Figure 4.1: Monthly rainfall trends in Finlays Saosa from December 2023 to March 2025

(Source: Secondary data from ARD Weather Station, Finlays)

The temperature data were also analyzed to assess the seasonal and annual variability that may influence wetland performance during the research period (Figure 4.2). On the graph, the y-axis represented the temperature values in °C, while the x-axis represented the months when the temperature levels were taken. Over the two years from December 2023 to March 2025, the average maximum temperature was 23.20°C, while the average minimum temperature was 11.1°C. Additionally, the highest maximum temperature of 25.9 °C was recorded in February 2025, which was within the study period, and the lowest maximum temperature was noted in July 2024, which is 21.3°C. Additionally, for the minimum temperature, the highest value of 12.43 °C was noted in April 2024, while the lowest, 9.87 °C, was recorded in December 2024, which was within the sampling period. Overall, the maximum temperature ranged between 22.81 °C to 24.32 °C, while the minimum temperatures ranged from 9.87 °C to 11.68 °C throughout the study duration.

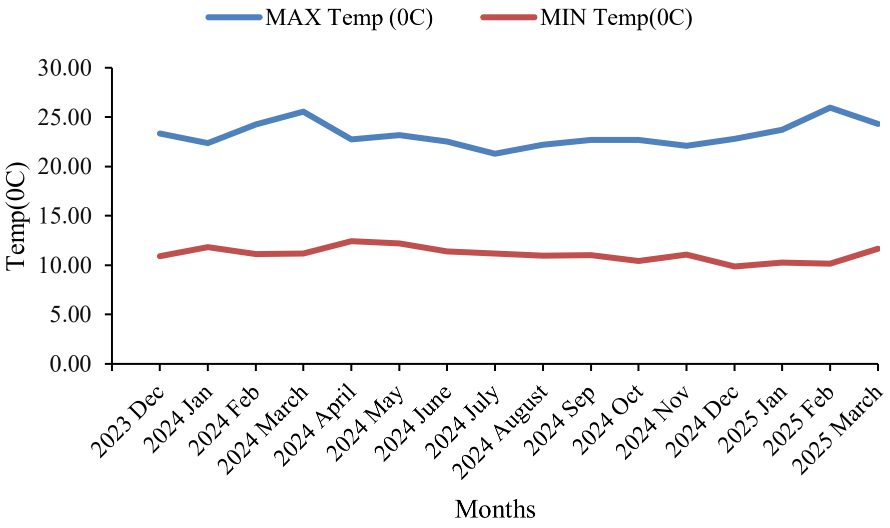

Figure 4.2: Temperature trends at the sampling sites from December 2023 to March 2025 (Source: ARD Weather Station Finlays)

4.1.2 Spatial variation of the physical parameters (pH, electrical conductivity, dissolved oxygen, water temperature, and Total Suspended solids (TSS)

Physical water quality indicators such as dissolved oxygen, pH, water temperature, electrical conductivity, and TSS vary throughout the wastewater treatment process. Sampling points during the fieldwork included; the raw influent directly from the tea factory (collected in the day channel sump), reed bed inlet, reed bed outlet, gravel bed outlet, Cell 1 outlet, Cell 2 outlet, and Cell 3 outlet (discharging to the soak pit) as summarized in Table 4.1.

Table 4.1: Spatial variation of physical measurements at Finlays Saosa constructed wetland during the study period

Physical parameters	DO(mg/L)	Temp(ºC)	(pH)	EC(µs/cm-^{1})	TSS (mg/L)
Raw influent	2.86 ± 1.22	31.48 ± 0.73^{a}	(6.62-9.49)	1129.71 ± 112.99^{a}	3794.18 ± 49.46^{a}
	(0.61-8.81)	(28.33-33.67)		(627.67-1585)	(3484.0-4060.0)
Inlet reed bed	5.23 ± 0.63	24.49 ± 0.34^{b}	(8.14 -9.68)	1446.90 ± 58.67^{b}	70.86 ± 13.83^{b}
	(1.87-7.14)	(23.4-25.8)		(1176.33-1665.67)	(12.00-172.00)
Outlet reed bed	3.75 ± 0.72	22.83 ± 0.50^{b}	(8.39 -9.46)	1418.90 ± 48.83^{b}	43.67 ± 7.11^{b}
	(1.19-5.86)	(20.9-24.47)		(1184.00-1593)	(12.00-92.00)
Gravel bed outlet	4.95 ± 0.44	23.07 ± 0.97^{b}	(8.63 -9.66)	1363.71 ± 53.72^{ab}	62.28 ± 11.19^{b}
	(2.63-6.02)	(20.27-26.63)		(1185.67-1583)	(8.00-160.00)
Cell 1 outlet	3.14 ± 0.34	21.52 ± 0.54^{bc}	(8.65 -9.62)	1294.38 ± 33.84^{ab}	30.29 ± 6.31^{b}
	(2.30-4.78)	(19.53-23.3)		(1172.33-1398)	(8.00-80.00)
Cell 2 outlet	3.17 ± 0.52	19.61 ± 0.27^{bc}	(9.19 -9.51)	1222.86 ± 28.74^{ab}	10.00 ± 2.39^{b}
	(0.97-5.25)	(18.9-20.7)		(1113.67-1336.33)	(0.00-28.00)
Cell 3 outlet	2.67 ± 0.62	19.4 ± 0.44^{bc}	(9.18- 9.81)	1168.95 ± 38.05^{ab}	7.69 ± 1.23^{b}
	(0.89-5.7)	(18.33-21.83)		(1046-1322)	(0.00-16.00)

N/B: Means followed with the same superscript letters are not significantly different, at p=0.05 level, whereas those with different letters indicate a significant difference (Tukey's HSD Test)

Data presented as mean ± SE, except for pH. The values in brackets represent the ranges (n =21 for other *in situ* parameters except TSS, where n = 14). DO values did not show a significant difference with the ANOVA test.

The mean DO concentration showed a general decline from the raw influent to the outlet of Cell 3, but the decline was not significantly different (ANOVA, F=2.181, d.f=6, p=0.064), indicating stable DO levels across the treatment stages. Therefore, we fail to reject the null hypotheses for DO, suggesting that the constructed wetland did not significantly alter the DO concentrations.

The average water temperature declined significantly along the wastewater treatment pathway (ANOVA, F=48.768, d.f=6, p=0.001), showing the largest temperature difference between the raw influent and Cell 3 outlet (Tukey's HSD test, mean difference = 12.07ºC, $p<0.001$). There were no statistically significant differences that were observed in the intermediate stages (Tukey’s HSD Test, $p>0.05$). Therefore, the results obtained support the rejection of the null hypotheses, confirming that water temperature significantly changed along the wastewater treatment pathway.

In terms of pH values, it ranged from 6.62-9.49 in the raw influent, which increased as the water flowed along the wastewater treatment pathway, and therefore, the Cell 3 outlet recorded a range of 9.18-9.81, which was the highest range. Electrical conductivity showed a statistically significant decrease through the treatment stages (ANOVA, F=4.288, d.f=6, p=0.002). The most marked decrease occurred between the raw influent and the inlet reed bed (Tukey's HSD test, mean difference = -317.19 µs/cm, p = 0.009) and between the raw influent and the outlet reed bed (Tukey's HSD test, mean difference = -289.19 µs/cm, p = 0.021). However, many differences between later treatment sites are not statistically significant, indicating that most ionic reduction occurred in the initial stages. Therefore, the findings support the rejection of the null hypotheses for electrical conductivity.

TSS demonstrated an incredibly significant decline across the wastewater treatment pathway (ANOVA, F=5515.55, d.f=6,p=0.001). The raw influent had a significantly higher TSS level than other sites (Tukey’s HSD test, mean difference = 3723-3784 mg/L, $p< 0.001$). Additionally, no significant differences were observed among subsequent treatment stages (Tukey’s HSD Test, $p>0.05$). Therefore, these results strongly reject the null hypothesis, illustrating effective TSS reduction through the wastewater treatment pathway.

4.1.3 Variation in chemical parameters (Biological oxygen demand (BOD_5), Chemical oxygen demand (COD), and tannins) across distinct locations

The average BOD_5 content varied significantly among the sampling points (ANOVA, F=6.015, d.f=6, p=0.001), demonstrating spatial differences in organic load across the sampling sites, as illustrated in Fig. 4.3. The y axis depicts the BOD_5 concentrations in mg/L, while the x axis indicates the sampling points. The greatest BOD_5 concentrations were found in the inlet reed bed, gravel bed outlet, and the raw influent, with average values of 1.01 ± 0.10 mg/L, 0.92 ± 0.07 mg/L, and 0.87 ± 0.22 mg/L, respectively, indicating the untreated nature of the incoming wastewater.

The outlet reed bed and Cell 1 outlet showed moderate BOD_5 concentration, ranging between 0.55 ± 0.05 and 0.72 ± 0.10 mg/L. The values gradually declined along the wastewater treatment pathway, with Cell 2 and 3 outlets having a mean BOD_5 concentration of below 0.39 ± 0.05 mg/L, indicating enhanced treatment performance at these stages. Additionally, the raw influent, inlet reed bed, outlet reed bed, gravel bed outlet, and Cell 1 outlet all had significantly higher values compared to outlets of Cell 2 and 3 (Tukey's HSD Test, $p<0.05$). However, there was no significant difference between the raw influent and other intermediate points (Tukey's HSD test, $p>0.05$). Additionally, there was no significant difference between the mean BOD_5 concentration of Cell 2 outlet and Cell 3 outlet (Tukey's HSD Test, $p>0.05$). This pattern indicates a steady but statistically significant drop in mean BOD_5, thereby supporting the rejection of the null hypotheses and confirming that BOD_5 levels varied significantly along the wastewater treatment pathway.

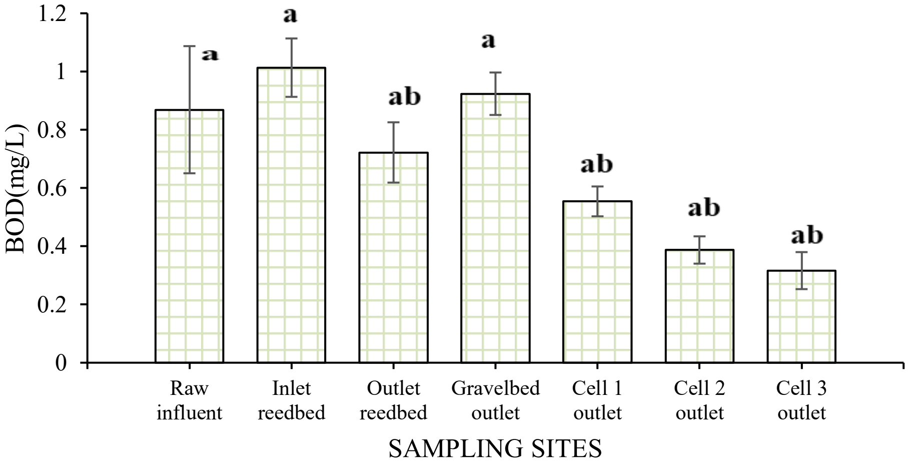

Figure 4.3: BOD_5 mean concentration in the sampling points (n=21).

Means followed by different letters on the bars show a significant difference, while means followed by the same letters are not significantly different.

COD concentrations showed a significant variation in their mean concentration across the sampling points (ANOVA, F=36.26, d.f=6, p=0.001), as shown in Fig. 4.4. The y-axis represents the COD concentration in mg/L, while the x-axis indicates the sampling points. The raw influent exhibited the highest mean COD concentrations of 3779.65 ± 588.12mg/L, which differed significantly from the other sampling points (Tukey's HSD Test, p<0.05). Following this, a sharp decline was recorded at the inlet reed bed, a concentration of 184.17 ± 24.83mg/L, indicating an initial high rate of organic load reduction. The decreasing trend continued along the wastewater treatment pathway, with the successive sampling points showing further reduction. The lowest mean COD concentration was recorded in Cell 2 outlet, a concentration of 62.67 ± 7.41mg/L, highlighting the effectiveness of the final treatment stages. However, after the initial drop of COD concentration in the raw influent, the later stages showed no significant differences (Tukey's HSD Test, p>0.05). Therefore, the findings lead to the rejection of the null hypotheses, confirming that COD concentrations significantly decreased along the wastewater treatment pathway, particularly between the raw influent and the inlet reed bed, with stable levels later.

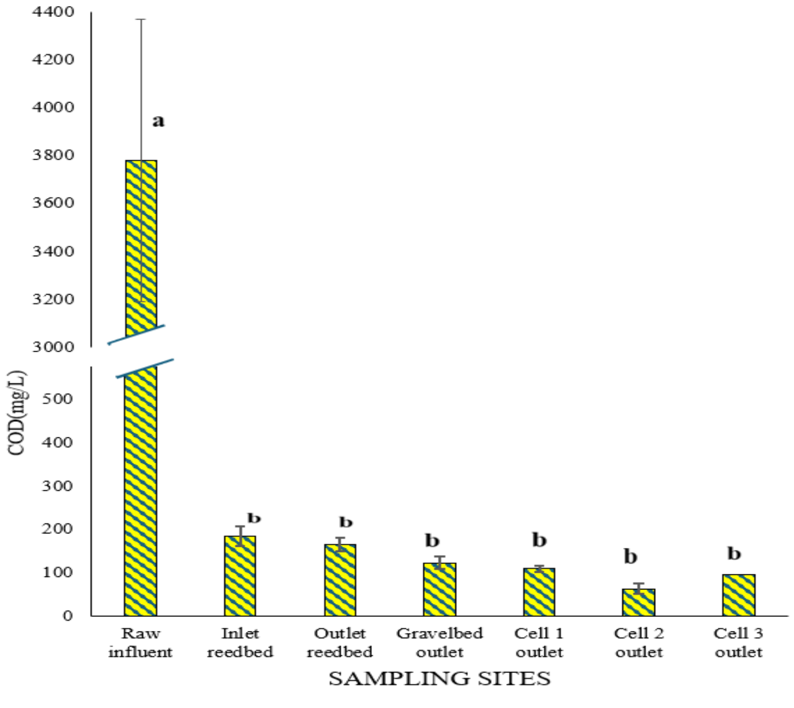

Figure 4.4: COD mean concentrations across the wastewater treatment pathway (n=21). Means followed by different letters on bars show a significant difference, and the means followed by the same letter are not significantly different.

The ratio of BOD and COD is frequently used to determine the biodegradability of organic compounds. A BOD/COD ratio of < 0.3 indicates that a substantial proportion of organic matter is resistant to degradation and may require more elaborate treatment. The

BOD/COD ratio was calculated based on the Biodegradable index, and in all the sampling points, the ratio was <0.3, as indicated in Table 4.2.

Table 4.2: BOD/COD ratio as an indicator of wastewater biodegradability at the sampling site

Site	COD (mg/L)	BOD (mg/L)	BOD/COD ratio
Raw influent	3779.65	0.87	0.0002
Inlet reed bed	184.17	1.01	0.005
Outlet reed bed	164.5	0.72	0.004
Gravel bed outlet	123.33	0.92	0.007
Cell 1 outlet	109.5	0.55	0.005
Cell 2 outlet	62.67	0.55	0.006
Cell 3 outlet	95.36	0.32	0.003

The mean tannin concentration varied significantly across the sampling points (ANOVA, F=73.72, d.f=6, p=0.001), as shown in the Figure. 4.5, where the y-axis shows the tannin concentrations in mg/L, and the x-axis represents the sampling points. The highest mean tannin concentration was observed at the raw influent at 0.40 ± 0.02mg/L, indicating a high initial tannin load. In contrast, the Cell 1 outlet recorded the lowest tannin concentration, 0.05 ± 0.01mg/L. Tukey's HSD test(p<0.05) showed that tannin concentration at the raw influent was significantly different from all other sampling points along the wastewater treatment pathway. However, no statistically significant differences were found among intermediate stages (Tukey's HSD Test, p>0.05. As a result, these findings support the rejection of the null hypotheses, confirming that tannin concentration significantly varied along the wastewater treatment pathway.

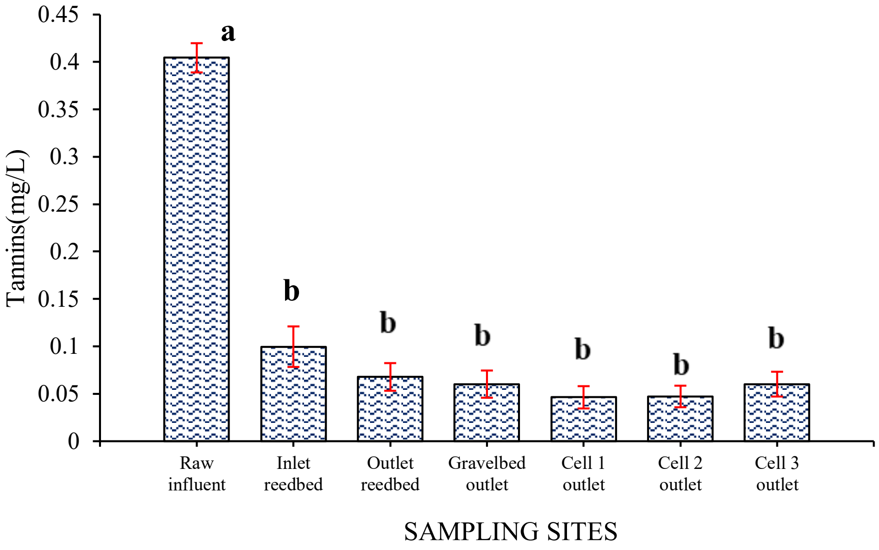

Figure 4.5: Tannin concentration in the selected sampling points (n=21).

Means followed by different letters on bars show a significant difference, and the means followed by the same letter are not significantly different.

4.1.4 Spatial trends of nutrients (ammonium, nitrite, nitrate, total nitrogen, soluble reactive phosphorus, total phosphorus) along the wastewater treatment pathway

Ammonium concentration showed significant differences across the sampling points (ANOVA, F = 4.07, d.f = 6, p = 0.001), as illustrated in Figure 4.6, where the y-axis indicates ammonium concentration (mg/L) and the x-axis represents the sampling points. Raw influent had a significantly higher ammonium concentration of 0.013 ± 0.002 mg/L, indicating a high organic load. At the same time, the Cell 3 outlet exhibited the lowest mean ammonium concentration of 0.003 ± mg/L, showing a significant reduction at the end of the treatment phase. The raw influent differed significantly from the other sampling points (Tukey's HSD Test, $p<0.05$), except the outlet reed bed (Tukey's HSD Test, $p>0.05$), showing that ammonium removal was less pronounced at the initial stages. Overall, there was a decreasing trend in ammonium concentration, with the most effective reduction occurring after the outlet reed bed and throughout the treatment cells. As a result, the findings strongly reject the null hypotheses, demonstrating that ammonium concentration varied significantly across the treatment stages and the system was effective in eliminating ammonium levels.

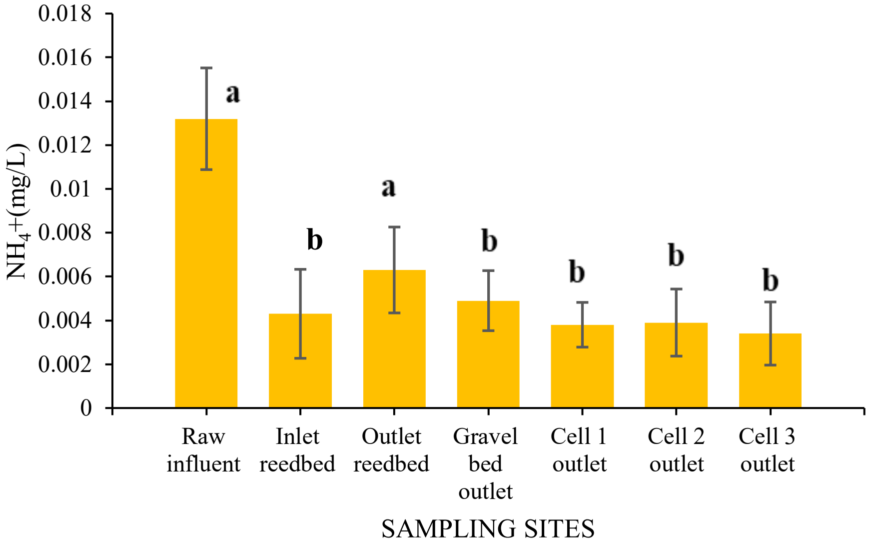

Figure 4.6: Mean ammonium concentration in the selected sampling points (n=21). Means followed by different letters on bars show a significant difference, and the means denoted by the same letter are not significantly different.

In terms of the nitrite concentration, it varied significantly along the wastewater treatment pathway (ANOVA, F=6.587, d.f =6, p=0.001) as presented in Figure 4.7, where the y-axis represents nitrite concentration (mg/L) and the x-axis denotes the sampling points. The raw influent recorded the highest mean nitrite concentration of 0.74 ± 0.15 mg/L, indicating a high initial load rate of nitrite in the untreated wastewater. In contrast, the Cell 3 outlet exhibited the lowest mean nitrite concentration of 0.13 ± 0.04 mg/L, indicating successive nitrite reduction at the end of the wastewater treatment pathway. There was a slight rise in nitrite concentration after the inlet reed bed, and was it was not significant and further reduced at the Cell 3 outlet. There were statistically significant differences between the raw influent and the other sampling points in terms of mean nitrite concentration (Tukey's HSD test, p>0.05), except among intermediate stages (Tukey's HSD test, p>0.05). This trend indicates that initial stages led to initial nitrite reduction, with the most notable decline occurring at the end of the treatment stages. Therefore, the findings lead to the rejection of the null hypotheses, demonstrating that nitrite concentration changed significantly along the wastewater treatment pathway, validating the system's overall efficacy in reducing nitrite levels.

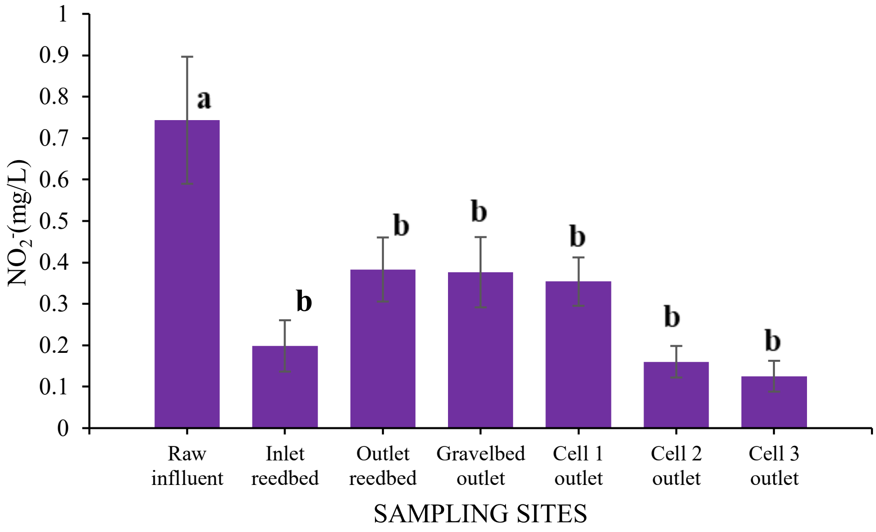

Figure 4.7: Mean nitrite concentration along the wastewater treatment pathway(n=21). Means followed by different letters on bars show a significant difference and the means denoted by the same letter are not significantly different.

Nitrate concentrations significantly varied across the site (ANOVA, F=3.021,d.f=6, p=0.008) as shown in Figure 4.8. The y-axis on the graph represented the nitrate concentration in mg/L and the x-axis showed the sampling points. While the overall variation was statistically significant, most pairwise comparisons across sampling points did not show statistically significant differences in mean nitrate concentration (Tukey's HSD Test, p>0.05). Cell 3 outlet was the only cell with a significant difference from other sampling points (Tukey's HSD Test, p>0.05). Additionally, Cell 3 outlet had the least mean nitrate concentration of 34.22 ± 2.67mg/L, indicating effective nitrate reduction towards the later treatment stages, whereas earlier stages revealed significantly larger and more stable concentrations. This pattern shows a downward trend in nitrate concentration along the wastewater treatment pathway, with a significant reduction occurring at the end stages. As a result, these findings reject the null hypothesis, confirming that nitrate concentration changed significantly across the treatment system with minimal spatial differences in intermediate sampling points.

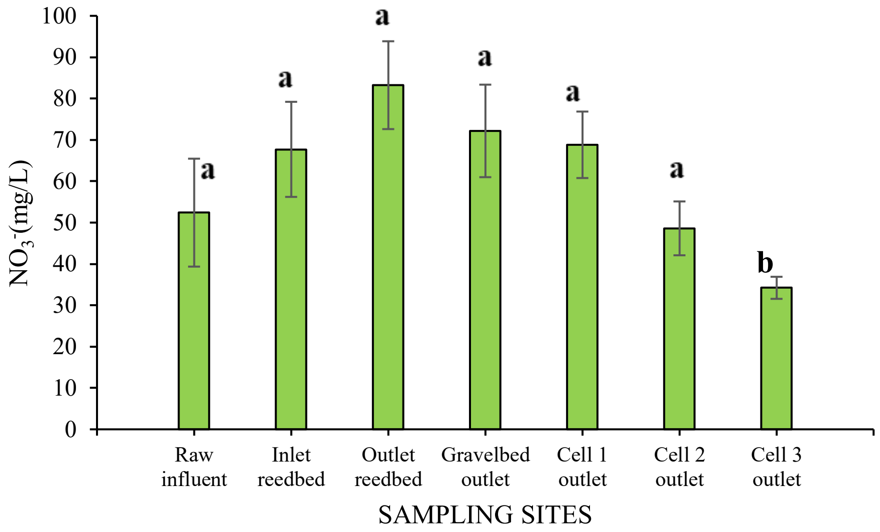

Figure 4.8: Mean nitrate concentrations along the wastewater treatment pathway (n=21). Means followed by different letters on bars show a significant difference, and the means denoted by the same letter are not significantly different.

There was a significant variation in TN concentration across the sampling points (ANOVA, F=2.936, d.f=6,p=0.01), as shown in Fig. 4.9. The x-axis shows the sampling points during the research, and the y-axis represents the total nitrogen concentration in mg/L. The outlet reed bed had the highest mean TN concentration, 83.60 ± 10.58 mg/L, suggesting a temporary accumulation or transformation of nitrogen compounds in this sampling point. In contrast, the Cell 3 Outlet recorded the lowest mean TN concentration of 34.35 ± 2.68 mg/L, indicating effective total nitrogen reduction in the final stages of the treatment system. Additionally, there was a statistically significant difference between other sampling points and the Cell 3 outlet (Tukey HSD Test, $p<0.05$), but there was no significant difference among other sampling points (Tukey HSD Test, $p>0.05$). This finding indicates a general downward trend in total nitrogen concentration along the wastewater treatment process, with the greatest reduction occurring at the final treatment cell. As a result, these results support the rejection of the null hypotheses, demonstrating that total nitrogen concentration significantly varied along the wastewater treatment pathway, even though most intermediate differences were not statistically significant.

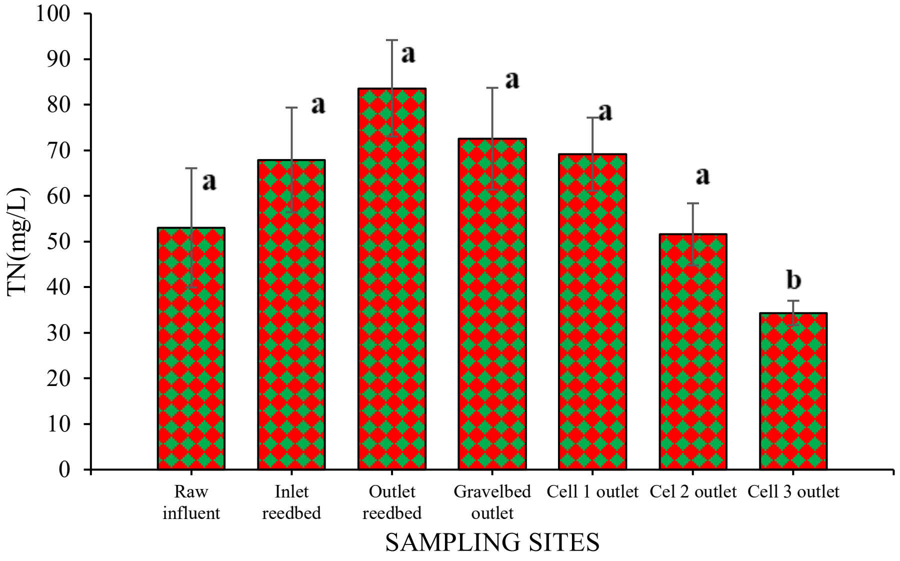

Figure 4.9: Total nitrogen concentrations in the sampling points (n=21).

Means followed by different letters on bars show a significant difference, and the means denoted by the same letter are not significantly different.

For the SRP concentration recorded in the sampling points, they varied significantly across those points (ANOVA, F=27.18, d.f.=6, p=0.001), as shown in Figure 4.10. On the graph, the y-axis represents the SRP concentrations (mg/L), while the x-axis indicates the sampling points. The raw influent had the highest mean SRP concentrations of 3.61 ± mg/L, significantly higher than other sampling points (Tukey HSD Test, $p < 0.05$), indicating a large SRP load entering the system. The mean SRP concentration was lower along the treatment pathway, and variation was little across the intermediate stages, from the inlet reed bed to the Cell 3 outlet, with no significant difference found among intermediate sampling points (Tukey HSD test, $p>0.05$). Therefore, this trend shows that most of the SRP reduction happened early in the treatment phase, with subsequent stages maintaining a consistent low concentration. These results reject the null hypothesis, illustrating effective SRP reduction via the wastewater treatment system.

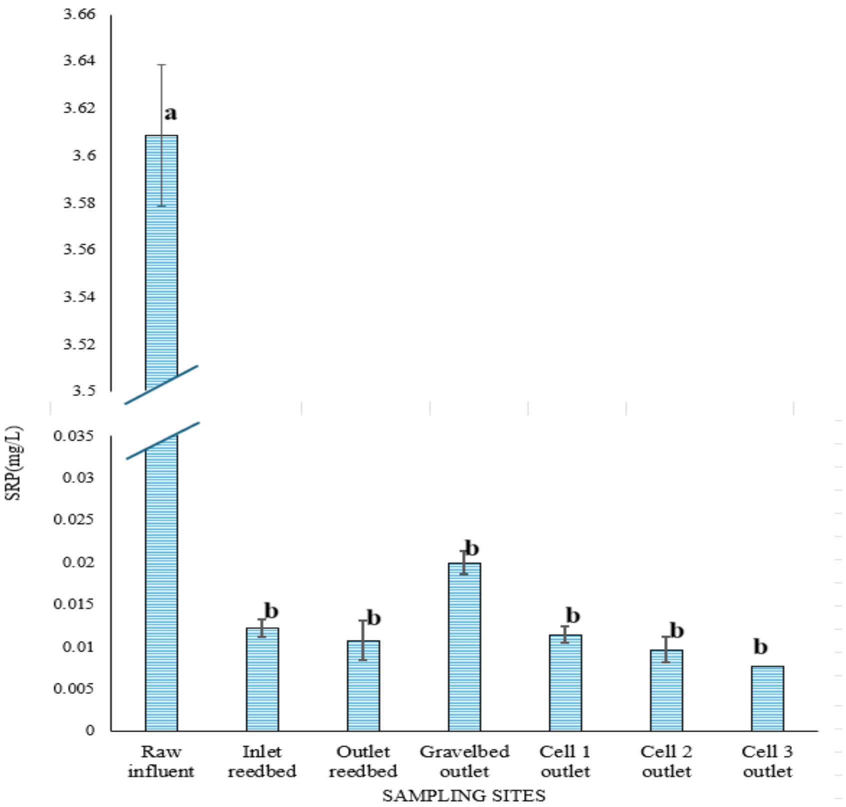

Figure 4.10: Mean SRP concentrations along the wastewater treatment pathway(n=21). Means followed by different letters on bars show a significant difference, and the means denoted by the same letters are not significantly different.

For total phosphorus, the concentration significantly varied across the sampling points (ANOVA, F=66.69, d.f =6, p=0.001), as seen in Figure 4.11. The y-axis represents the TP concentrations in mg/L, while the x-axis indicates the sampling points. Raw influent recorded the highest mean TP concentration of 0.26 ± 0.03mg/L, indicating a significant TP load into the system. In contrast, Cell 3 Outlet had the lowest mean TP concentration of 0.006 ± 0.0005mg/L, indicating significant phosphorus removal at the final stages of the wastewater treatment pathway. Additionally, a significant difference was observed between the raw influent and all other sampling points (Tukey HSD Test, $p<0.05$), but no significant difference between the successive treatment phases (Tukey HSD Test, $p>0.05$). This showed a consistent phosphorus level reduction after the initial treatment. Therefore, these results support the rejection of the null hypotheses, confirming that TP concentration significantly decreased along the wastewater treatment pathway, highlighting the effectiveness of the system in total phosphorus removal.

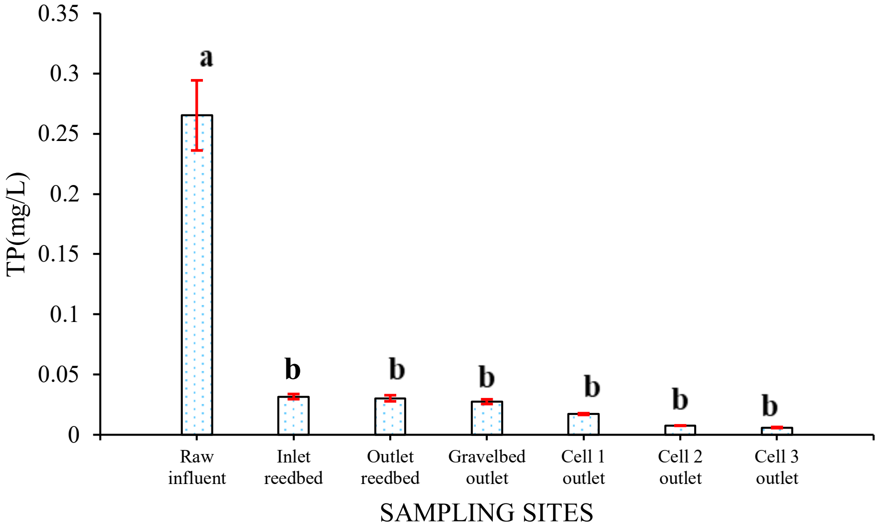

Figure 4.11: Total phosphorus spatial variation in the sampling points. (n=21).

Means followed by different letters on bars show a significant difference, while the means followed by the same letter are not significantly different.

4.2 Macrophytes’ above-ground biomass and evaluation of the potential of different macrophytes for nutrient removal in the constructed wetland

4.2.1 Vegetation cover in Finlays Saosa constructed wetland

Finlays Saosa constructed the wetland’s vegetation inventory, which was designed to improve treatment efficacy by establishing macrophyte zones. The wetland consists of five treatment cells with varying vegetation cover levels shown in Table 4.3. Additionally, the distribution and density of macrophytes vary geographically and seasonally, with vegetation thriving during the rainy season and decreasing during the dry season, indicating hydrological and biological responses.

In terms of vegetation composition and cover per cell, the reed bed cell was the first cell and was dominated by *Phragmites mauritianus*. Additionally, the cell was designed to have a high biomass and dense covering, allowing for primary sedimentation and pollutant uptake. *Phragmites mauritianus* remains dominant, covering around 75% of the cell and ranking 5 on the Braun-Blanquet scale. Additionally, the gravel bed cell was the second cell, and was intended for primary filtration and water cleaning, and was intentionally left sparsely vegetated. Currently, it has a rank of 1 and barely 2% cover, consisting of scattered *Canna indica* plants.

On the other hand, Cell 1 was the third cell and was designed for secondary treatment.

Additionally, the system was meant to support moderate vegetation development while also serving as an algae pond. Currently, it has approximately 65% cover (rank 4), with *Pontederia cordata* as the main plant species. Other plant species in the cell include *Canna indica* and *Cyperus alternifolius*, which have grown especially along the margins during the wet season. Without forgetting, Cell 2 was the fourth cell and was designed to host a diverse macrophyte community while simultaneously serving as an algal pond. It presently supports around 40% cover (rank 3), with *Juncus effusus* and *Colocasia esculenta* growing along the margins.

Cell 3 was the final polishing cell in the wastewater treatment pathway. It has grown into a dense macrophyte zone with a cover of around 75% (rank 5). The dominating plant species is *Cyperus papyrus*, followed by *Typha latifolia*, *Nymphaea spp*. (water lily), *Cyperus alternifolius* and *Colocasia esculenta*.

Table 4.3: Vegetation cover ranking in Finlays Saosa Constructed wetland using the Braun-Blanquet scale

Braun-Blanquet rank	**Vegetation cover (%)**	**Cell description**
1	0% vegetation cover <5%	Gravel bed cell (2%)
2	5% ≤ vegetation cover <25%	-
3	25%≤ vegetation cover <50%	Cell 2 (40%)
4	50% ≤ vegetation cover <75%	Cell 1(65%),
5	75% ≤ vegetation cover <100%	Reed bed cell (75%), Cell 3 (75%)

(Source: Kent, 2012)

4.2.2 Macrophytes above-ground biomass

Several types of macrophytes present in Finlay's Saosa CW showed notable variability in the above-ground biomass as shown in Table 4.4, indicating differences in ecological adaptation, growth form, and functionality. *Pontederia cordata* had the highest dry weight of 8986.01 ± 2.21 g/m², followed by *Juncus effusus* with a biomass of 8227.99 ± 68.77 g/m². Additionally, *Colocasia esculenta* also showed a high biomass of 6031.46 ± 0.50 g/m². Without forgetting, *Cyperus alternifolius* and *Phragmites mauritianus* recorded moderate above-ground biomasses of 3801.84 ± 0.68 g/m² and 3836 ± 22.24 g/m², respectively. In contrast, *Typha latifolia* and *Cyperus papyrus* exhibited comparatively lower biomasses of 3072.16 ± 0.91 g/m² and 3532.86 ± 1.12 g/m², while *Canna indica* had the lowest dry weight of 2592.13 ± 4.28 g/m².

Table 4.4: Macrophyte above-ground biomass in g/m² of Finlay's Saosa constructed wetland
(Data presented as mean ± SE)

Macrophyte species	**Macrophyte above-ground biomass in g/m²**
Phragmites mauritianus	3836,48 ± 22,24
Canna indica	2592,13 ± 4,28
Pontederia cordata	8986,01 ± 2,21
Cyperus alternifolius	3801,84 ± 0,68
Juncus effusus	8227,99 ± 68,77
Colocasia esculenta	6031,46 ± 0,50
Cyperus papyrus	3532,86 ± 1,12
Typha latifolia	3072,16 ± 0,91

4.2.3 Macrophyte nutrient removal in Finlays Saosa constructed wetland

Macrophyte nutrient removal for the above-ground biomass of different macrophytes in Finlays Saosa constructed wetland is presented in Table 4.5**.** The phosphorus removals ranged from 4.15 g/m^2 to 17.49 g/m^2, with *Colocasia esculenta* having the highest phosphorus removal rate of 17.49 g/m^2 and *Canna indica having* the lowest phosphorus removal rate of 4.15g/m^2. Additionally, the nitrogen removal ranged from 5.75g/m^2 to 62.9g/m^2, with *Pontederia cordata* having the highest nitrogen removal rate of 62.9g/m^2 and *Phragmites mauritianus* having the lowest removal rate of 5.75g/m^2.

Table 4.5: Macrophyte percentage of nutrient removal in Finlays Saosa constructed wetland

Plant species	**P removal (g/m^2)**	**N removal (g/m^2)**
Phragmites mauritianus	9.21	5.75
Canna indica	4.15	15.81
Pontederia cordata	17.07	62.9
Cyperus alternifolius	8.36	23.95
Juncus effusus	13.16	37.03
Colocasia esculenta	17.49	35.59
Cyperus papyrus	14.48	13.07
Typha latifolia	6.76	15.36

4.3 Determining the efficiency of the Finlays Saosa constructed wetland in treating pretreated tea extract wastewater

The mean influent and effluent loadings, together with the concentration of several parameters in the Finlays Saosa constructed wetland, along with their percentage removal effectiveness, are shown in Table 4.6. The loadings of each pollutant varied along the wastewater treatment pathway during the research. Additionally, inlet loadings were higher and decreased at the CW's outlet. The pollutant removal efficiency ranged from 98.33% to 99.72%.

Finlays Saosa constructed wetland demonstrated an impressive performance in eliminating all the pollutants, achieving over 98% reduction across all the monitored parameters. TSS, TP, BOD_5, SRP, nitrate, TN, tannins, nitrite, COD, and ammonium showed removal efficiencies of 99.72%, 99.50%, 99.29% ,99.00%, 98.74%, 98.73%, 98.57%, 98.52%, 98.70%, and 98.33%, respectively, indicating the system's effectiveness in organic matter and nutrient removal.

Table 4.6: General pollutant removal efficiency at Finlays Saosa constructed wetland during the research period, with n as the sample size

Parameters	**n**	**CW inlet(mg/L)**	**CW outlet(mg/L)**	**CW inlet (Kg/day)**	**CW outlet (Kg/day)**	**%Removal Efficiency (Loading)**
COD	21	184.2	95.36	254.59	3.295	98.70
BOD_5	21	1.01	0.32	1.40	0.01	99.29
NH_4^+	21	0.004	0.003	0.006	0.0001	98.33
TSS	14	70.86	7.69	97.95	0.27	99.72
NO_2^-	21	0.20	0.13	0.27	0.004	98.52
NO_3^-	21	67.71	34.22	93.59	1.18	98.74
SRP	21	0.012	0.008	0.02	0.0002	99.00
TP	21	0.03	0.006	0.04	0.0002	99.50
TN	21	67.91	34.355	93.88	1.19	98.73
Tannins	21	0.10	0.06	0.14	0.002	98.57

When the effluent concentrations were compared with the Kenya NEMA set standards, as shown in Table 4.7, TSS, TP, and BOD_5 met the NEMA standards for effluent discharge to the environment. COD and TN did not meet the standards. COD final effluent concentration was 95.36 mg/L compared to the NEMA standard of 50 mg/L while TN effluent concentration was 34.35mg/L compared to the guideline value of 2mg/L.

Table 4.7: Kenya NEMA standards for effluent discharge into the environment

Parameters	**Kenya NEMA standards (mg/L)**
COD	50
BOD_5	30
$^*NH_4^+$	-
TSS	30
$^*NO_3^-$	-
$^*NO_2^-$	-
*SRP	-
TP	2 (Guideline value)
TN	2 (Guideline value)
*Tannins	-

Note: * means not indicated in Kenya NEMA standards
(Source: Environmental Management and Coordination (Water Quality) Regulation, 2006)

The percentage efficiency of pollutant removal per cell is shown in Table 4.8. The reed bed was the best in removing all the pollutants, with a removal efficiency of above 75%. On the other hand, Cell 3 outlet was the second best in terms of removal efficiency, with all the pollutants having a removal efficiency of above 68 %. Additionally, Cell 2 was the third in ranking in terms of pollutant removal, whereby, only 3 pollutants were removed from the cell at an efficiency of above 50%, that is, TSS, TP, and NO_2^- with 66.98%, 55.81%, and 54.70% removal efficiency, respectively. For Cell 1, it did not perform well in terms of pollutant removal since all the pollutants were below 50%, except for only one pollutant, that is, TSS, with 51.38%. The gravel bed cell was poor in terms of pollutant removal, and the removal efficiency of all the pollutants was below 50%.

Table 4.8: Comparative ranking and percentage removal efficiency of pollutants across Finlays Saosa constructed wetland cells

Rank	**Cells in the CW**	**% Efficiency of pollutant removal per cell**										**Number of pollutants with more than average removal rate**
		COD	BOD_5	NH_4^+	TSS	NO_2^-	NO_3^-	SRP	TP	TN	Tannin	
1	Reed bed	90.51	92.43	84.43	93.45	79.50	86.94	90.67	89.84	86.92	92.78	10
2	Cell 3	69.56	83.66	82.56	84.62	84.36	85.92	83.92	84.21	86.69	74.49	10
3	Cell 2	42.77	30.13	-2.63	66.98	54.70	29.37	15.65	55.81	25.40	-1.94	3
4	Cell 1	11.22	40.03	22.45	51.38	6.017	4.66	42.50	37.46	4.67	23.09	1
5	Gravel bed	11.79	-50.51	8.50	-67.81	-15.63	-2.01	-117.86	-6.78	-2.10	-4.46	0

CHAPTER FIVE

DISCUSSION

5.1 Variation in physical, chemical, and nutrient parameters with their influence on the efficiency of a constructed wetland

5.1.1 Weather characteristics in the study area

Weather conditions have a significant impact on the performance and efficiency of CWs, primarily affecting parameters such as temperature, rainfall, dissolved oxygen, hydraulic retention time (HRT), and the hydraulic loading rate. (HLR). Over the past two years, Finlay's Saosa has undergone significant climate variability, which has impacted the constructed wetland's functionality and efficiency. The peaks and troughs of the bar graphs illustrate the region's seasonal variations. The average annual rainfall of 201.94 mm was recorded, and seasons with high rainfall, such as April 2024 with rainfall of 381 mm, may have caused temporary dilution of the incoming wastewater, resulting in improved influent quality. However, significant rainfall can exceed the system's design capacity, limit HRT, and lower treatment efficiency (Lawrence *et al.*,2024a). Such hydrological pressures can also resuspend settled sediments, introducing increased concentrations of COD and TSS in the CW Lawrence *et al.*, 2024a), while decreasing ammonia concentrations by dilution. When the storm water is not controlled properly, it can overload the system, and later, the CW fails.

Temperature is another key factor that influences the biological performance of a CW. Figure 4.2 shows the temperature range recorded in the Automated Rainfall and Data (ARD) weather station, with the minimum temperature ranging between 9.87 to 11.68°C, and the maximum temperature ranging from 22.81°C to 24.32°C. These changes have an impact on microbial activity, which is the critical component of most CW treatment performance. As stated by Li *et al.* (2023), while lower temperatures can impede microbial metabolism and limit the decomposition of organic matter, higher temperatures can induce heat stress on microbial populations, reducing microbial efficiency. In that conjunction, adaptive management solutions are required to ensure consistent treatment results, despite seasonal temperature variations (Li *et al.*, 2023). Pfeifer and Otto (2023) state that colder seasons can disturb microbiological processes, posing operational challenges. Therefore, to maintain consistent treatment efficiency, especially during extreme weather conditions, adaptive management strategies are essential (Lawrence *et al.*, 2024b). This includes implementing storm flow containment methods to reduce hydraulic surges during the rainy seasons, integrating shading and insulation mechanisms to optimize temperature conditions, thus safeguarding the functional stability of the CWs (Lawrence *et al*., 2024b).

5.1.2 Spatial variation of the physical parameters and their influence on the constructed wetland treatment efficiency

When the physical parameters vary throughout the wastewater treatment pathway, it affects the CW performance in treating the wastewater. This occurs in physical parameters like dissolved oxygen (DO), water temperature, pH, EC, and TSS. The chemical and biological processes involved in pollutant removal are affected by the variation of the physical parameters. As a result, knowing and understanding this variation is critical for improving wetland performance and biological function. Therefore, this section investigates the spatial variation of these parameters across the sampling points within the treatment system.

During the research, DO gradually declined from the raw influent with a concentration of 2.86 ±1.22mg/L to the Cell 3 outlet, with a concentration of 2.67 ±0.62mg/L. However, there was no statistically significant difference in the sampling points. The raw influent recorded the lowest dissolved oxygen concentrations, attributed to the large organic load in the untreated wastewater. Additionally, microorganisms consumed dissolved oxygen to degrade organic matter and to conduct respiration, lowering its concentration (Stensel *et al*., 2014). Conversely, the high dissolved oxygen concentration in the inlet reed bed could be due to the presence of Finlays wastewater treatment plant, which partially treats wastewater before it is released to the wetland through the inlet reed bed, reducing the dissolved oxygen consumption. Therefore, the organic load will be reduced, and thus dissolved oxygen concentration will be less used, thus remaining high. Additionally, proper aeration in the treatment plant reduces the dissolved oxygen consumption. DO concentrations decrease slightly in the outlet reed bed, due to oxygen consumption by microbes in organic matter decomposition. On the other hand, the gravel bed outlet also displayed a high dissolved oxygen concentration due to aeration conditions in the cell. Additionally, the presence of biofilm in the cell that may contain algae or oxygen-producing organisms increases DO concentrations (Kadlec and Wallace, 2008). Subsequent reductions in DO concentration in the last 3 sampling points could be attributed to oxygen consumption due to microbial activity in those cells.

In the day channel sump, where the wastewater was held, direct sunlight penetration caused the raw influent to have a higher temperature concentration of 31.48°C than other sites; however, this concentration dramatically dropped along the wastewater treatment pathway. The shade of macrophyte plants caused cooling effects, resulting in a 12.07°C difference between the raw influent and the Cell 3 outlet. Effective thermal buffering allowed comparatively steady temperatures in the phases that followed the raw influent. These findings aligned with (Fuller *et al*., 2022), who claimed that heat dissipation through substrate interaction and the shadowing effects of emerging plants are the main causes of temperature decrease in wetlands.

The pH value in the raw influent ranged from 6.62-9.49 and increased significantly to a range of 9.18-9.81 in the Cell 3 outlet. The neutral to slightly acidic pH values in the raw influent may be attributed to the cleaning agents, such as the detergents used in the tea factory, which raised the pH of the influent and buffered the system toward a neutral condition. Additionally, the biological activity in the raw influent could be slow, particularly aerobic processes, and thus the pH remained neutral or reduced (Mohamed *et al*., 2021). Conversely, the pH values of subsequent stages increased to an alkaline state and remained stable. This could be due to photosynthetic conditions, due to adequate light exposure and nutrient availability, particularly in the Cell 1 and Cell 2 outlets, where algae absorb CO_2, reducing carbonic acid in water and increasing pH (Mohamed *et al*., 2021). Additionally, the ammonium (NH_4^+) can volatilize into ammonia gas (NH_3^-), which can escape into the atmosphere, while consuming hydrogen ions in the process, thus raising the pH (Vymazal, 2011).

In terms of electrical conductivity on the sampling points, although the concentration in the inlet reed bed increased to 1446.90 ± 58.67 µs/cm, the study found that the EC concentration decreased along the wastewater treatment pathway, from raw influent with a concentration of 1129.71 ± 112.99 µs/cm to Cell 3 outlet with EC of 1168.95± 38.05 µs/cm. The low quantities of inorganic salts and ions are responsible for the low EC values in the raw influent. On the other hand, microbial decomposition of organic matter releases ions and salts in water, increasing EC (Headley *et al*., 2005). Additionally, plant roots excrete ions, increasing EC concentration in the rhizosphere. Furthermore, nitrification of ammonium to nitrate adds more ions to water, further increasing EC (Vymazal, 2011).

In the early phases of treatment before effluent release, researchers have discovered that organic matter breakdown and nitrogen compounds transformation can momentarily raise the EC concentration (Etsuyankpa *et al*., 2024). However, efficient ion removal through substrate adsorption, dilution, plant uptake, microbial activity, and precipitation causes the concentration of EC to drop in succeeding cells. (Vymazal, 2011) highlighted how vegetation absorption and hydraulic retention time can lower EC levels in horizontal subsurface flow wetlands.

The raw influent had a high TSS concentration compared to the constructed wetland influent, due to a high concentration of suspended particles from tea factories and nearby farms, but it decreased rapidly at other sites. This is due to the presence of the conventional wastewater treatment facility's ability to remove these suspended particles through filtration and sedimentation led to a larger reduction in TSS concentration in the inlet reed bed. On the other hand, the outflow reed bed receives its water from the reed bed cell that contains reeds, which remove TSS through filtration by plant roots and substrate and microbial activity, resulting in a significant decrease in TSS. These findings are consistent with those of Kadlec and Wallace (2008), whereby they stated that well-designed constructed wetlands and reed beds can dramatically reduce TSS concentrations while improving the water quality. Therefore, TSS removal in the CW is achieved through sedimentation and filtration in the plant roots and substrate (Guan *et al.*, 2015).

Gravel bed outlet had a greater TSS concentration than the other sampling stations, except for the raw influent, resulting in negative percentage removal. This could be because of clogging in the substrate pores, as shown by the resurfacing flow in some parts of the cell. Additionally, the development of biofilm and organic debris buildup from microbial activity could have caused the exit pipes to clog (Tanner, 1995). Furthermore, the biological and physical processes occurring within the other succeeding cells caused the TSS concentration to gradually drop, lowering the amount of suspended solids in those sampling points (UN-HABITAT, 2008).

5.1.3 Chemical parameters variation along the wastewater treatment pathway and their influence on the efficiency of the constructed wetland

Chemical parameters, such as BOD_5, COD, and tannins, are important indicators of organic pollution in the environment. In this study, the parameters were used to assess how effective the constructed wetland is in treating tea extract wastewater.

BOD_5 concentrations varied significantly between sampling points. This revealed that organic matter was effectively removed at some stages. This is supported by Kadlec and Wallace (2008), who documented the efficacy of subsurface flow wetlands in lowering BOD_5 concentrations through microbial decomposition and physical filtration. There was no significant difference in BOD_5 concentration between the raw influent and the early stages, such as inlet reed bed, gravel bed outlet, outlet reed bed and Cell 1 outlet suggests a limited immediate impact on the initial treatment of components of biodegradable organic load, such as tea leaves and polyphenol compounds, which are resistant to microbial degradation (Etsuyankpa *et al.*, 2024). The slow but statistically significant drop in BOD_5 concentrations in the last cell outlets (2 and 3) can be attributed to increased microbe retention time for organic matter degradation. Furthermore, Cell 2 is an algal pond with algae that release oxygen during the day, and the microorganisms use oxygen to decompose organic matter, lowering BOD_5 concentrations in the Cell 2 outlet. Also, emergent plants in Cell 3, such as *Phragmites australis*, carry oxygen from the atmosphere to the root rhizosphere, where microbes use oxygen to decompose organic matter, lowering BOD_5 levels in the Cell 3 outlet. Additionally, vertical subsurface flow wetlands can improve oxygen transport used in organic matter decomposition (Wu *et al.*, 2014).

COD concentrations decreased significantly along the wastewater treatment pathway, with a sharp decline from raw influent to the inlet reed bed. This could be due to high initial biodegradable and non-biodegradable organic load, whose source can be phenols and complex tannins found in tea processing effluents (Okorie *et al.*, 2011). The significant drop in COD levels in the subsequent stages could be due to the sedimentation process in the conventional wastewater treatment facility, substrate adsorption, and some partial microbial degradation that took place in those cells (Okorie *et al.*, 2011). Additionally, the uniform COD concentrations in the latter treatment phases indicated that many biodegradable and non-biodegradable organic components were eliminated earlier in the process. This finding is consistent with Chao *et al.* (2005), who found that multi- stage constructed wetlands successfully reduce COD, particularly when the system incorporates vertical and horizontal subsurface flow, encouraging aerobic and anaerobic conditions in the system.

Evaluating the biodegradability of organic matter is critical for determining the viability of biological treatment procedures in a constructed wetland. This is typically accomplished by comparing the BOD and COD concentrations using the biodegradability index. The index is commonly stated as the BOD/COD ratio, and it indicates how quickly organic compounds can be broken down biologically. According to Metcalf and Eddy (2003), a BOD/COD ratio of more than 0.5 suggests strong biodegradability, while values between 0.3 and 0.5 indicate moderate biodegradability. In addition, a ratio <0.3 indicates low biodegradability, indicating the existence of non-biodegradable organic compounds that require additional treatment, as shown in Table 5.1.

Table 5.1: Interpretation of the biodegradability index values

Biodegradability index value	Interpretation	Biodegradability
>0.5	High biodegradability , appropriate for biological treatment	High
0.3-0.5	Moderate biodegradability	Moderate
<0.3	Low biodegradability requires physical, chemical, or advanced treatment	Low

Source: (Metcalf and Eddy, 2003)

COD and BOD_5 were compared at various sampling points along the constructed wetland, and the resulting BOD / COD ratios were consistently below 0.3, as presented in Table 4.2. The results show that a large amount of organic debris in the tea extract effluent is resistant to biological degradation. The low BOD/COD ratio is caused by the presence of polyphenols and tannins in the tea extract wastewater, which inhibit microbial activity or resist decomposition (Stensel *et al*.,2014). To increase total biodegradability, pretreatment such as advanced oxidation and a longer retention time are necessary to minimize organic load in wastewater (Sato *et al*., 2013).

Tannin concentrations decreased significantly along the wastewater treatment pathway, with a statistically significant decline from the raw influent to the inlet reed bed, demonstrating the system's capacity for early-stage tannin removal. The raw influent had the highest mean tannin concentration of 0.40 ± 0.02mg/L, while the Cell 1 outlet had the lowest concentration of tannins,0.05± 0.01mg/L. A Tukey HSD test ($p<0.05$) confirmed that tannin levels at the raw influent differed significantly from other sampling points along the treatment pathway. However, no significant difference was observed in the intermediate phases ($p>0.05$), showing that successive cells contributed little to additional tannin decrease after the initial treatment. These findings are like those of Abira *et al.* (2008), who found that constructed wetlands have the highest removal efficiency of polyphenol compounds like tannins in the early compartments, where sedimentation and rapid adsorption by plant litter and microbial biofilm are most active.

The successful reduction in tannin concentrations in the inlet reed bed could be a result of increased microbial degradation in the wastewater treatment plant, resulting in a high rate of BOD_5 removal. The findings obtained are compatible with those of Reddy *et al* (1999), who reported that tannin elimination occurs in constructed wetlands via substrate adsorption, root zone filtration, and microbial decomposition. The steady status of tannin elimination in subsequent stages shows that either the system has reached a saturation point for tannin adsorption or the microbial populations in the downstream cells are less efficient at tannin breakdown. García *et al*. (2010) found that tannin molecules attach to organic compounds, forming stable complexes that inhibit microbial degradation. Additionally, the subsequent cells from the reed bed to the outlet cells played a role in polishing other pollutants, maintaining the stability of the system.

5.1.4 Nutrient variation on different sampling points in the constructed wetland and their influence on the efficiency of the system

Nutrient concentration varied along the wastewater treatment pathway, indicating the effectiveness of the constructed wetland at various treatment stages. The study found that ammonium concentrations decreased significantly along the treatment pathway, with raw influent having the highest concentration of 0.013 ± 0.002mg/L and Cell 3 outflow having the lowest, that is,0.003 ± 0.001mg/L. Additionally, the high ammonium concentrations in the raw influent were due to the high organic nitrogen load and low oxygen concentration, which triggers the ammonification process, inhibiting the nitrification process in raw wastewater, thus ammonium accumulation (Marek *et al*., 2021). Additionally, the high ammonium concentration in the reedbed outlet may be due to anoxic conditions, excess organic matter that consumes oxygen, leaving little oxygen for nitrifiers, and low plant density in the reed bed cell, particularly during the dry season, reducing oxygen transfer.

Ammonium removal from constructed wetlands is frequently impacted by nitrification efficiency and oxygen availability (Akratos & Tsihrintzis, 2007). The ammonium concentration in other cells was low, due to high oxygen concentration in algal ponds, where algae release oxygen during photosynthetic activity, long hydraulic retention time, and the intake of ammonium by algae for growth (Vymazal, 2011). Alternatively, the gravel bed cell provided surface area for aerobic nitrifier colonization and biofilm production, improving nutrient cycling and nitrogen removal (Kadlec and Wallace, 2008).

For the nitrite concentrations, there was a significant decrease along the treatment pathway with a rapid decline from the raw influent to Cell 3 outlet. The raw influent exhibited a high nitrite concentration, which might be attributed to inadequate nitrification caused by low dissolved oxygen concentration (Stensel *et al.*, 2014). On the other hand, the subsequent cells exhibited low nitrite concentrations due to complete nitrification in algal ponds or denitrification processes in gravel-bed cells with anaerobic zones (Vymazal, 2007). Additionally, macrophyte plants eliminated some of the nitrite via plant absorption in those cells. Some researchers, such as Kadlec and Wallace (2008), discovered that nitrite is rapidly converted under alternating aerobic and anaerobic circumstances, which are common in wetlands.

Nitrate concentrations varied significantly across the treatment system in Finlays Saosa, with notable changes between all other sites and the Cell 3 outlet. This pattern represents a typical nitrogen transformation in a constructed wetland. From the raw influent to the outlet reed bed, high and increasing nitrate levels suggest active nitrification, where ammonium is transformed to nitrite and nitrate by nitrifying bacteria under aerobic situations (Brix, 1997). Furthermore, the nitrate concentration remained stable from the outlet reedbed to the Cell 2 outlet, indicating that nitrification continues but is partially balanced by partial denitrification, preventing microorganism zones with low oxygen levels conducive to denitrifying bacteria from reducing nitrates (Vymazal, 2007).

Reduction in nitrate concentration at the Cell 3 outlet could be attributed to an effective denitrification process, which was facilitated by longer retention time and more pronounced anoxic conditions. This process allowed nitrates to be converted to nitrogen gas, removing nitrogen from the system (Tanner, 2001). These findings are consistent with those of Vymazal (2010), who discovered that the latter phases of a multi-stage constructed wetland system frequently function as key zones for nitrogen removal via denitrification processes.

The TN concentration varied along with the wastewater treatment system, with Cell 3 having lowest quantities of 31.35 ± 2.68mg/L. In addition, there was a significant difference between Cell 3 outlet and other sample points ($p<0.05$), but no significant difference between the other sampling points ($p>0.05$). The increase in TN content as water moves from the raw influent to the outlet reed bed could be attributed to nitrogen release from organic matter decomposition by microorganisms, the release of nitrogen compounds from root exudates, or inadequate nitrogen removal by macrophytes (Brix,1997). In contrast, the significant reduction in TN concentration in other cells from the outlet reed bed, particularly in Cell 3, may be attributed to effective nitrogen removal, possibly through a combination of nitrification and denitrification processes, plant uptake, long retention time in the cells, and filtration and sedimentation, particularly in the gravel bed cell (Kadlec & Wallace, 2008). Similar findings were reported by Vymazal (2007), who emphasized the importance of hydraulic retention time and plant species in increasing nitrogen removal effectiveness in CWs. Furthermore, multi-stage constructed wetlands with a mixture of aerobic and anaerobic zones promote full nitrogen transformation and removal (Kadlec and Wallace (2008).

SRP levels differed between sites, with raw influent having the highest concentration of 3.60 ± 0.65mg/L. Additionally, the subsequent sampling points showed no significant differences in SRP concentrations. The high SRP level in the raw influent could be attributed to the presence of high phosphorus content found in the tea extract wastewater, the use of the cleaning agents that are rich in phosphorus, and the microbial decomposition of organic matter, which releases phosphorus into the wastewater as SRP (Zheng *et al.*, 2019). Additionally, SRP levels were reduced significantly in the inlet reed bed and the outlet reed bed. This could be because of removal processes such as adsorption in the substrate medium found in the reed bed cell, plant uptake, and the macrophyte harvest as biomass (Vymazal, 2007).

Gravel bed outlet had more SRP concentration than the other sampling points, except for the raw influent. Reasons could be phosphorus release from the sediments/gravel in the cell, and desorption from the saturated substrates back to the water (Vymazal,2007). Furthermore, anaerobic conditions in the gravel bed cell can break down iron-bound phosphorus, releasing SRP into the water body (Reddy *et al.*, 1997). Additionally, SRP was decreased stably across the subsequent treatment cells (from Cell 1 to Cell 3 outlets), with the lowest values recorded at the last sampling point. This could be due to processes such as plant uptake, microbial assimilation, long retention time, and SRP dilution by water (Vymazal,2007). Such findings are supported by Vymazal (2007), who showed that multi-stage constructed wetlands can improve SRP removal effectiveness when compared to a single-cell system due to longer retention time and a more diverse microenvironment.

In terms of TP concentration, it varied significantly along the wastewater treatment pathway, decreasing from raw influent to the Cell 3 outlet. The raw influent had a higher TP concentration than the subsequent cell. This could be because of the nature of the tea extract from the factory, which has elevated levels of organic matter and nutrients, particularly phosphorus compounds from the factory cleaning agents, and fertilizers used during tea production (Wu *et al.*,2014). This revealed that most of the total phosphorus removal happened during the initial stages before effluent was directed to the reed bed. Wu *et al.* (2014) support this trend of total phosphorus removal, pointing out that horizontal subsurface flow constructed wetlands often achieve most of the phosphorus removal in the system's initial stages. Furthermore, there was a significant decrease in TP levels at consecutive sample stations following the raw influent, showing successful phosphorus removal across the wetland system. The drop in TP content could be attributed to macrophyte uptake in the constructed wetland, especially for the emergent macrophytes, during the peak growing seasons (Vymazal, 2007). Other processes that can result in the drop in TP concentration include adsorption by the substrate and sedimentation in the cells, particularly the reedbed and the gravel bed (Kadlec and Wallace, 2008). The significance of substrate is especially important in constructed wetlands with media rich in iron, aluminum, or calcium, which can precipitate phosphorus as insoluble compounds (Kadlec and Wallace, 2008).

5.2 Macrophytes' above-ground biomass and the evaluation of the potential of different macrophytes for nutrient removal in the constructed wetland

5.2.1 Vegetation cover in Finlays Saosa constructed wetland

The cover of vegetation in CW is critical in terms of wastewater treatment and pollutant removal. The vegetation removes the pollutants through processes such as sedimentation, filtration, nutrient uptake, and microbial interactions (Vymazal,2011). Therefore, the wetland's zone design, with five treatment cells and variable vegetation structure, is an important ecological method to enhance treatment performance.

Reed bed cell was the first in the sequence of the wastewater treatment pathway, and was dominated by *Phragmites mauritianus*, which had over 75% plant cover, demonstrating its high biomass potential and significant contribution to sedimentation and nutrient absorption. Its first growth benefits especially during the wet season, aiding in primary treatment by reducing TSS in the water (Vymazal, 2011). Additionally, the developing root zones in the plant for microbial attachment aid in the transfer of oxygen used in nitrification and denitrification. In contrast, the gravel bed cell, which was the second cell in the sequence, was purposefully created with less vegetation to facilitate primary filtration. However, because of its substrate type and low nutrient retention, the gravel cell had minimal vegetation cover of 2 % and a rank of 1, with limited plant establishment. These findings are consistent with those of Tanner (2001), who found that substrate composition had a substantial impact on the macrophyte colonization in a constructed wetland.

Cell 1, the third in the sequence, was an algal pond and had a plant cover of 65% and a rank of 4. *Pontederia cordata*, *Canna indica,* and a few *Cyperus alternifolius* were the dominant plant species. This was consistent with Keizer-Vlek *et al*. (2014) findings, who discovered that *Pontederia cordata*, particularly in the rainy season, exhibits strong lateral spread in a nutrient-rich wetland environment. This level of vegetation density strikes a balance between promoting algal growth and maintaining macrophyte-based nutrient cycling, making it suitable for secondary treatment, which reduces organic matter and nutrients (Kadlec and Wallace,2008).

Cell 2 had the same functional significance as Cell 1, supporting both algae and macrophyte communities, with 40% plant cover and a rank of 3. It was covered by *Juncus effusus* and *Colocasia esculenta* around the margins, showing moderate nutrient uptake capacity and bank stability, which contributed to overall system resilience, particularly in variable seasons. The findings are supported by Vymazal (2011), who discovered that *Juncus effusus* is typically found in wetlands with moderate patches.

Finally, Cell 3 had a high vegetation cover of 75%, a rating of 5, and served as a polishing cell. *Cyperus papyrus* dominated, with a few species of *Colocasia esculenta*, *Typha latifolia*, (Nymphaea spp.) water lily, and *Cyperus alternifolius*. The abundance and density of vegetation in this final cell facilitate the removal of remaining nutrients and pathogens via a combination of physical, chemical, and biological processes (Akratos and Tsihrintzis, 2007). Overall, the spatial variation in vegetation across the wetland demonstrates careful ecological design to enhance treatment efficiency at each stage, and seasonal dynamics highlight the importance of adaptive management measures to sustain performance throughout the year.

5.2.2 Macrophyte above-ground biomass in Finlays Saosa constructed wetland

The study at Finlays Saosa constructed wetland discovered that macrophytes' above-ground biomass differed between plant species, indicating changes in ecological adaptation, growth form, and functional roles within the treatment system. *Pontederia cordata* had the highest above-ground biomass of 8986.01 ± 2.21 g/m^2, due to its efficient nutrient absorption, hence faster growth, adaptability to changing weather conditions, broad leaves for photosynthesis, and reduced susceptibility to illness and herbivory. This finding corresponds to that of Yang *et al*. (2025), who observed that, *Pontederia sp* often exhibit rapid growth and large biomass accumulation due to their photosynthetic efficiency and tolerance to nutrient-rich conditions. On the other hand, *Juncus effusus* had a high biomass of 8227.99 ± 68.77 g/ m^2, and this could be because of tolerance to fluctuating water levels and the ability to live in both aerobic and anaerobic zones (Brix, 1997). *Colocasia esculenta* also had a high biomass of 6031± 0.50 g/m^2, suggesting its capacity to thrive in a nutrient-rich, wet environment. Its large leaf surface area enhances transpiration while also aiding in evapotranspiration (Brix, 1997).

Among the emergent macrophyte species present in the wetland, *Cyperus alternifolius*, *Phragmites mauritianus*, *Typha latifolia*, and *Cyperus papyrus* showed moderate above-ground biomass levels of 3801 ± 0.68 g/m^2, 3836 ± 22.24 g/m^2, 3072.16 ± 0.91 g /m^2, respectively. Reasons are their tolerance to wetland environments and the presence of a broad fibrous root system with higher metabolic activity (Vymazal, 2007). The plant species also allocate a substantial portion of their energy and resources to the below-ground biomass, particularly in wetland habitats (Vymazal, 2007). Additionally, these species can withstand fluctuations in water levels, allowing for long- term growth despite variation in nutrients and oxygen concentrations (Tonderski *et al*., 2005). On the other hand, *Canna indica* had the lowest above-ground biomass of 2592.13 ± 4.28 g/m^2 due to its tolerance to saturated soils and nutrient-rich environmental conditions, limiting its growth (Brisson and Chazarenc, 2009).

5.2.3 Macrophyte nutrient removal in Finlays Saosa constructed wetland

For the macrophytes that were present in Finlay's Saosa constructed wetland, they varied significantly in terms of nutrient removal and nutrient removal, highlighting the importance of plant species selection in enhancing phytoremediation in the constructed wetland. *Colocasia esculenta* and *Pontederia cordata* exhibited the highest phosphorus removal of 17.49g/m^2 and 17.07 g/m^2, respectively. This is consistent with Akrantos and Tsihrintzis (2007) discovery that species with broad leaves and first development rates absorb more phosphorus due to their high nutrient intake and translocation process. *Juncus effusus* and *Cyperus papyrus* also revealed significant P removal of 13.16g/m^2 and 14.48 g/$m^{2,}$ respectively, which is consistent with previous research indicating that these plant species are effective in low-oxygen wetland soils where phosphorus is commonly retained in plant tissues or bound in root-associated sediments (Brix, 1997).

In comparison, *Canna indica* had the lowest phosphorus removal rate of 4.15g/m^2.

According to Cui *et al*. (2010), the plant's short root structure and low above-ground biomass limit its ability to absorb phosphorus. Of interest, *Phragmites mauritianus,* which is widely used in constructed wetlands because of its high biomass, removed only 9.21g/m^2 of phosphorus. While Brix (1997) recognized *Phragmites mauritianus* as effective in some hydrological settings, its efficiency in P removal varies with substrate type, the system design, and the plant maturity.

For the nitrogen removal, some plant species, such as *Pontederia cordata, Juncus effusus,* and *Colocasia esculenta* with a removal efficiency of 62.9g/m^2, 37.03g/m^2, and 35.59g/m^2 respectively, had higher removal rates. *Pontederia cordata,* superior nitrogen removal is consistent with Li *et al.* (2023) findings, who attributed its success to increased oxygen availability to the rhizosphere and support for the nitrifying and denitrifying bacteria. Additionally, nitrogen removal in wetlands is driven by processes such as nitrification and denitrification, which are facilitated by the plants that transfer oxygen from the atmosphere to the rhizosphere (Reddy *et al*., 1989). In addition, *Juncus effusus*, with its high above-ground biomass, demonstrated a high nitrogen removal rate, due to its root architecture and nutrient absorption capacity, with the dense root mat providing an ideal environment for microorganisms to thrive (Tanner, 2001).

Cyperus alternifolius performed well in nitrogen removal, supporting Wu *et al.* (2014) findings, that such plant species can boost nitrogen removal due to their tolerance to saturated conditions and root-induced oxygen release. Despite being less successful in phosphorus removal, *Canna indica* had a high nitrogen removal rate of 15.81 g/m^2, which could be attributed to its ability to maintain a denitrifying microbial population under changing environments (Vymazal, 2007). On the other hand, *Typha latifolia,* which is also widely used in wetland environments, showed moderate nitrogen removal of 15.36g/m^2, which is consistent with Vymazal's (2007) discovery, that *Typha sp* have varied nitrogen removal rates based on the seasons and system design.

On the other hand, *Phragmites mauritianus* removed just 5.75g/m^2 of nitrogen, the lowest of the species, contradicting other studies, including Brix (1997), which found that *Phragmites mauritianus* improved nitrogen removal through rhizosphere oxygenation. The lesser performance in this case could be attributed to site-specific restrictions such as limited aeration and low microbial activity.

5.3 Efficiency of Finlays Saosa-constructed wetland in treating pretreated tea wastewater

Loading efficiency, expressed in kg/day, measures the amount of pollutants removed over time, providing information about the system's ability to manage varying hydraulic and pollutant loads (Kadlec and Wallace, 2008). Metric is useful in real-world applications because it accounts for both the temporal and spatial variation in the influent characteristics. From this research, loading efficiency confirms that there was a significant decrease in pollutant loadings detected from the inlets to the outlets, across the measured parameters in the constructed wetland, confirming the system's efficacy in treating tea extract wastewater. Of the pollutants removed in the constructed wetland, TSS had the highest removal rate of 99.72%, whereas ammonium had the lowest removal rate of 98.33%.

The high efficiencies demonstrated that the system successfully integrates physical, biological, and chemical processes such as sedimentation, adsorption, microbial degradation, and plant uptake to remove the pollutants. Additionally, the high COD and BOD_5 removal efficiency of 99.29% and 98.70% demonstrates the CW's ability to eliminate organic compounds that are resistant to microbial degradation. These findings are consistent with Vymazal's (2011) observation that horizontal subsurface flow wetlands can achieve high COD and BOD removal rates above 90% under optimal loading conditions. Similarly, Wu *et al.* (2014) showed that full-scale CWs treating agricultural and industrial effluents removed more than 95%.

In terms of nutrient removal, Finlays CW achieved excellent results in removing TP and SRP with removal efficiencies of 99.50% and 99.00%, respectively. This could be attributed to both adsorptions on the substrate surfaces and uptake by macrophytes, which is like the findings of Kadlec and Wallace (2008), who emphasized the importance of substrate type and vegetation in phosphorus retention. Nitrate, TN, and ammonium were also effectively eliminated, with removal efficiencies of 98.74%,98.73%, and 98.33%, respectively. This could be attributed to microbial degradation processes and plant uptake, reducing their concentrations. One important finding was the system's tannin removal effectiveness of 98.57%. Given that tannins are often resistant to biological degradation, their removal was achieved through a mix of adsorption, sedimentation, and microbial degradation (Vymazal, 2007).

The examination of Finlays Saosa constructed wetland, with NEMA set standards, sheds light on the effectiveness of the CW in treating pre-treated tea extract effluent. When the effluent concentrations were compared with the NEMA suggested thresholds, several parameters, such as TSS, TP and BOD_5 with effluent concentrations of 7.69mg/L, 0.006 mg/L, 0.32mg/L met the set standards. This suggests that the system was particularly effective in removing TSS and phosphorus compounds through sedimentation, plant uptake, and adsorption (Kadlec & Wallace, 2009).

COD and TN with effluent concentrations of 95.36mg/L and 34.36mg/L, respectively did not meet the NEMA discharge standards for each parameter. High COD values may also indicate the presence of slowly degradable organic matter, thus persisting in the wetland (Vymazal,2007). The discharge of the final effluent into a forested soak pit may provide additional COD and TN removal. However, this was not investigated in the study.

Overall, these findings suggest that assessing pollutant loadings in addition to concentration data provides a more complete picture of the treatment capability of constructed wetlands. This technique is consistent with the suggestions of Tanner *et al.* (2001) and Brix (1997), who underlined the need to include flow-based mass balances in wetlands performance assessments, particularly in systems that treat fluctuating or industrial wastewater.

Table 5.2: Removal efficiencies of pollutants in selected wastewater treatment systems

Study location and system	TSS removal (%)	BOD_5 removal (%)	COD removal (%)	TP removal (%)	NH_4^+ removal (%)	NO_3^- removal (%)	TN removal (%)	REFERENCE
Chinga Tea factory (Constructed wetland)	90.3	47.5	53.2	65.4	35.2	42.1	40.7	Mwaka, S. N. (2017).
Eberege Tea factory (Conventional system)	96.8	73.4	68.9	78.2	45.6	58.3	55.7	Mwaka, S. N. (2017).
Kambaa Tea factory (Biofilter system)	100.0	90.9	90.9	85.0	60.0	55.0	50.0	Muthoni, M. N., & Wambua, J. K. (2007).
Chemerei constructed wetland in Finlays flower farm	98.1	69.5	57.2	93.6	98	88.6	88.6	Moshi, G. D. (2015)
Finlays Saosa constructed wetland	99.7	99.3	98.7	99.5	98.3	98.7	98.7	This study

For the different cells, the pollutant removal efficiency per cell in Finlays Saosa constructed wetland revealed some spatial variability. The reedbed cell exhibited the highest pollutant removal efficiency, with all the pollutants having a removal efficiency of above 75%. These results align to those of Brix (1997), who stressed the role of macrophytes in nutrient uptake, aeration of the rhizosphere, and zones of attachment of microorganisms involved in organic matter decomposition. Additionally, Cell 3 followed closely in terms of pollutant removal, with all the pollutants having a removal efficiency of 68% and above. This indicates that the cell, being the polishing cell based on the design of the CW in Finlays, plays a major part in nutrient removal through processes such as plant uptake, long retention time, adsorption, and microbial decomposition (Kadlec & Wallace, 2008).

Cell 2 was the third in the sequence of pollutant removal efficiency, showing moderate performance by removing three pollutants with a removal efficiency of above 50%. This could be due to the nature of the cell, which is an algal pond containing algae that conduct photosynthesis, releasing oxygen used by microorganisms in the decomposition of organic matter, thereby partially removing pollutants (Vymazal, 2007). On the other hand, Cell 1 was less effective, with only TSS, having a removal efficiency of above 50%. This could be due to still high loads in the cell, exceeding its removal capacity, combined with a short retention time in the cell.

The gravel bed cell performed poorly in removing all the pollutants. This could be due to cell blockage by suspended particles impeding filtration, resulting in resurfacing water in parts of the cell (UN-HABITAT,2008). Additionally, anaerobic conditions in the cell reduce its functionality in pollutant removal, together with short retention time and sparse vegetation, reducing its ability in pollutant removal (Butler *et al*., 2020).

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

i. There was a clear spatial variation in the physical, chemical, and nutrient parameters along the wastewater treatment pathway of Finlays Saosa, with significant reductions of most pollutants across the sampling points. This showed that the wetland system gradually improves water quality along the pathway. Therefore, this study supports the rejection of the null hypotheses ($H_0 1$).

ii. The above-ground biomass of the macrophytes demonstrated variation in capacity for nutrient storage, with certain species, such as *Pontederia cordata*, having higher above-ground biomass and nitrogen removal capacity. This variation emphasized the importance of plant selection in optimizing wetland performance. As a result, the null hypotheses ($H_0 2$) is rejected.

iii. The constructed wetland system at Finlays Saosa efficiently reduced all pollutants with some parameters such as TSS, TP and BOD_5 meeting the Kenya NEMA set standards except for TN and COD, which did not meet the set standards, thereby supporting its suitability for sustainable wastewater management. Therefore, this research rejects the null hypotheses ($H_0 3$).

6.2 Recommendations

i. Given the observed spatial variation and significant pollutant reduction along the treatment pathway, Finlays Saosa constructed wetland has demonstrated efficiency in improving wastewater quality. To sustain and improve its performance, there is a need for continuous spatial monitoring and optimization of the flow distribution, hydraulic loading rates, and maintenance schedules to achieve consistently high treatment efficiency. Since the study was conducted during the dry season, there is a need to also collect data during the wet season for comparison purposes. Additionally, there is a need to assess the quality of water after the soak pit before it flows to the river.

ii. There is a need to prioritize cultivation and maintenance of macrophytes with high nutrient uptake capacity, such as *Pontederia cordata* and *Colocasia esculenta*, to enhance nutrient removal and support wetland sustainability. Additionally, there is a need to research plant biomass temporal dynamics and establish the optimal period for harvesting for effective nutrient removal. On the other hand, more research needs to be done on why *Cyperus papyrus* had a lower nutrient removal rate compared to the suggested priority plants for cultivation.

iii. There is a need for the establishment of a long-term monitoring and adaptive management approach to maintain and enhance wetland treatment efficiency. This should include investigating the cause of flow resurfacing in the gravel bed cell, unclogging of the gravel bed cell, increasing the vegetation cover in the gravel bed cell, and increasing the frequency of harvesting of the macrophyte species in Cell 3. Additionally, submerged macrophytes can be introduced in Cell 3 to absorb dissolved nutrients in water.

6.3 Suggestions for further research

i. There is a need to study the effects of seasonal dynamics on wetland performance.
ii. Further research should be undertaken on microbial diversity and their roles in pollutant removal.
iii. The need to assess effectiveness of the soak pit past treatment wetland .

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APPENDICES

Appendix A: Mean values and Standard Errors(SE) of nutrients in different sampling points in Finlay's Saosa constructed a wetland

Sites	**Raw influent**		**Inlet reed bed**		**Outlet reed bed**		**Gravel bed outlet**		**Cell 1 outlet**		**Cell 2 outlet**		**Cell 3 outlet**	
Variables (mg/L)	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**
Ammonium	0.013	0.002	0.004	0.002	0.006	0.002	0.005	0.002	0.004	0.001	0.004	0.002	0.003	0.001
Nitrite	0.743	0.153	0.198	0.062	0.383	0.077	0.376	0.085	0.354	0.058	0.160	0.038	0.125	0.037
Nitrate	52.403	13.052	67.705	11.497	83.229	10.623	72.168	11.188	68.806	8.038	48.599	6.511	34.222	2.666
Total nitrogen	53.02	13.06	67.913	11.464	83.597	10.583	72.55	11.162	69.164	8.008	51.596	6.800	34.35	2.681
SRP	3.601	0.649	0.012	0.002	0.011	0.001	0.020	0.002	0.012	0.001	0.010	0.001	0.008	0.001
TP	0.265	0.029	0.032	0.002	0.030	0.003	0.028	0.002	0.017	0.001	0.008	0.000	0.006	0.000

Appendix B: Chemical parameters in the different sampling points together with their mean values and Standard Errors (SE)

Sites	**Raw influent**		**Inlet reed bed**		**Outlet reed bed**		**Gravel bed outlet**		**Cell 1 outlet**		**Cell 2 outlet**		**Cell 3 outlet**	
Variables (mg/L)	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**
BOD	0.87	0.22	1.013	0.10	0.72	0.10	0.92	0.07	0.55	0.05	0.39	0.05	0.32	0.06
COD	3779.65	588.12	184.17	24.84	164.50	22.54	123.33	15.36	109.50	13.83	62.67	7.41	95.37	12.36
Tannins	0.40	0.02	0.01	0.02	0.07	0.02	0.06	0.01	0.05	0.01	0.05	0.01	0.06	0.01

Appendix C: Different macrophyte species that were harvested during the research period

Cyperus papyrus

Cyperus alternifolius

Phragmites mauritianus

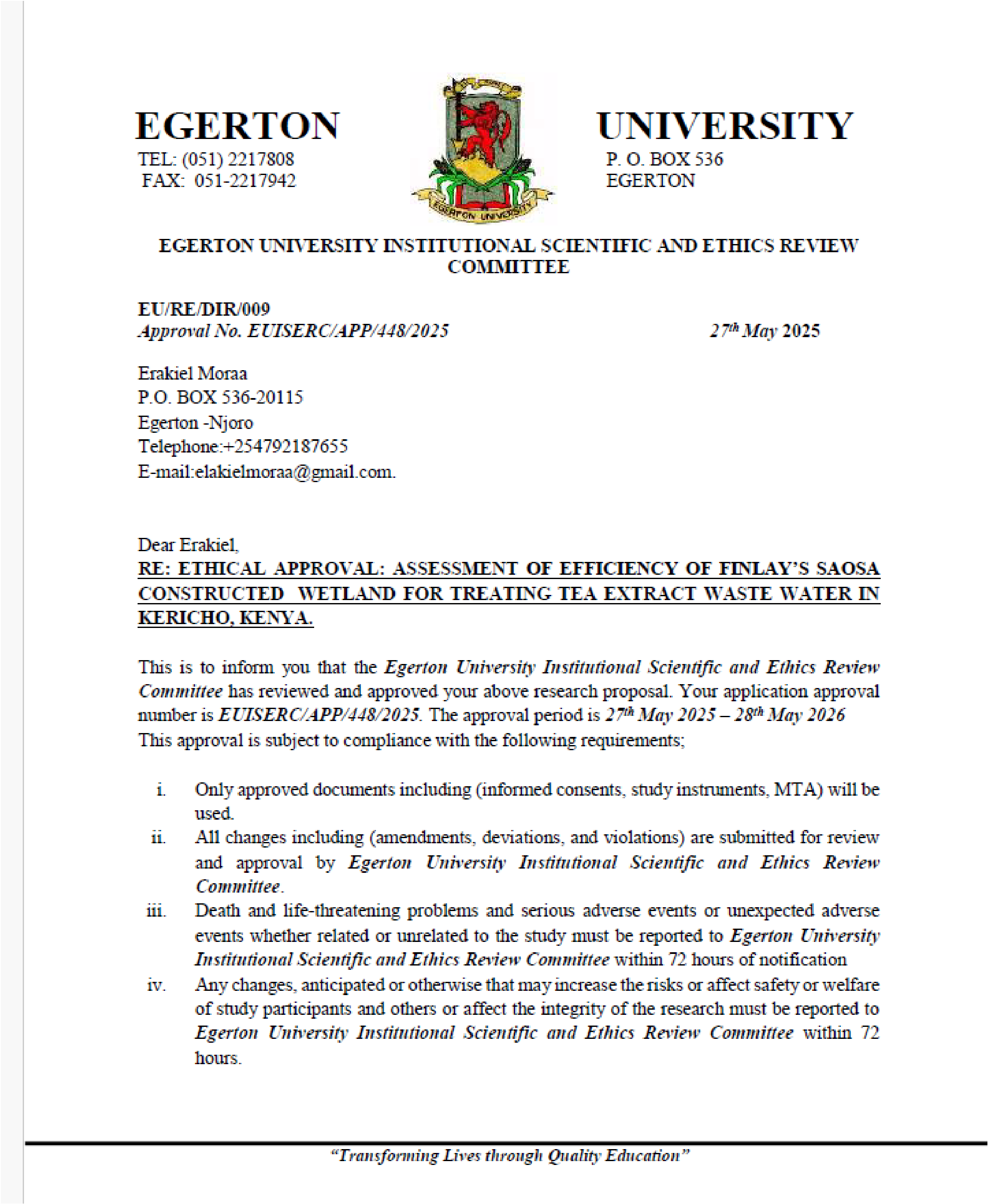
Canna lily

Pontederia cordata (Prickel weed)

Colocasia esculenta

Juncus effusus

Appendix D: Ethical clearance certificate issued by Egerton University, Institutional Scientific and Ethics Review Committee (EUISERC) for proposal approval



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EGERTON UNIVERSITY INSTITUTIONAL SCIENTIFIC AND ETHICS REVIEW COMMITTEE

EU/RE/DIR/009
Approval No. EUISERC/APP/448/2025 *27th May* **2025**

Erakiel Moraa
P.O. BOX 536-20115
Egerton -Njoro
Telephone:+254792187655
E-mail:elakielmoraa@gmail.com.

Dear Erakiel,
RE: ETHICAL APPROVAL: ASSESSMENT OF EFFICIENCY OF FINLAY'S SAOSA CONSTRUCTED WETLAND FOR TREATING TEA EXTRACT WASTE WATER IN KERICHO, KENYA.

This is to inform you that the *Egerton University Institutional Scientific and Ethics Review Committee* has reviewed and approved your above research proposal. Your application approval number is *EUISERC/APP/448/2025*. The approval period is *27th May 2025 – 28th May 2026*
This approval is subject to compliance with the following requirements;

i. Only approved documents including (informed consents, study instruments, MTA) will be used.
ii. All changes including (amendments, deviations, and violations) are submitted for review and approval by *Egerton University Institutional Scientific and Ethics Review Committee*.
iii. Death and life-threatening problems and serious adverse events or unexpected adverse events whether related or unrelated to the study must be reported to *Egerton University Institutional Scientific and Ethics Review Committee* within 72 hours of notification
iv. Any changes, anticipated or otherwise that may increase the risks or affect safety or welfare of study participants and others or affect the integrity of the research must be reported to *Egerton University Institutional Scientific and Ethics Review Committee* within 72 hours.

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v. Clearance for Material Transfer of biological specimens must be obtained from relevant institutions.

vi. Submission of a request for renewal of approval at least 60 days prior to the expiry of the approval period. Attach a comprehensive progress report to support the renewal.

vii. Submission of an executive summary report within 90 days upon completion of the study to ***Egerton University Institutional Scientific and Ethics Review Committee***.

Prior to commencing your study, you will be expected to obtain a research license from National Commission for Science, Technology and Innovation (NACOSTI) https://oris.nacosti.go.ke and also obtain other clearances needed.

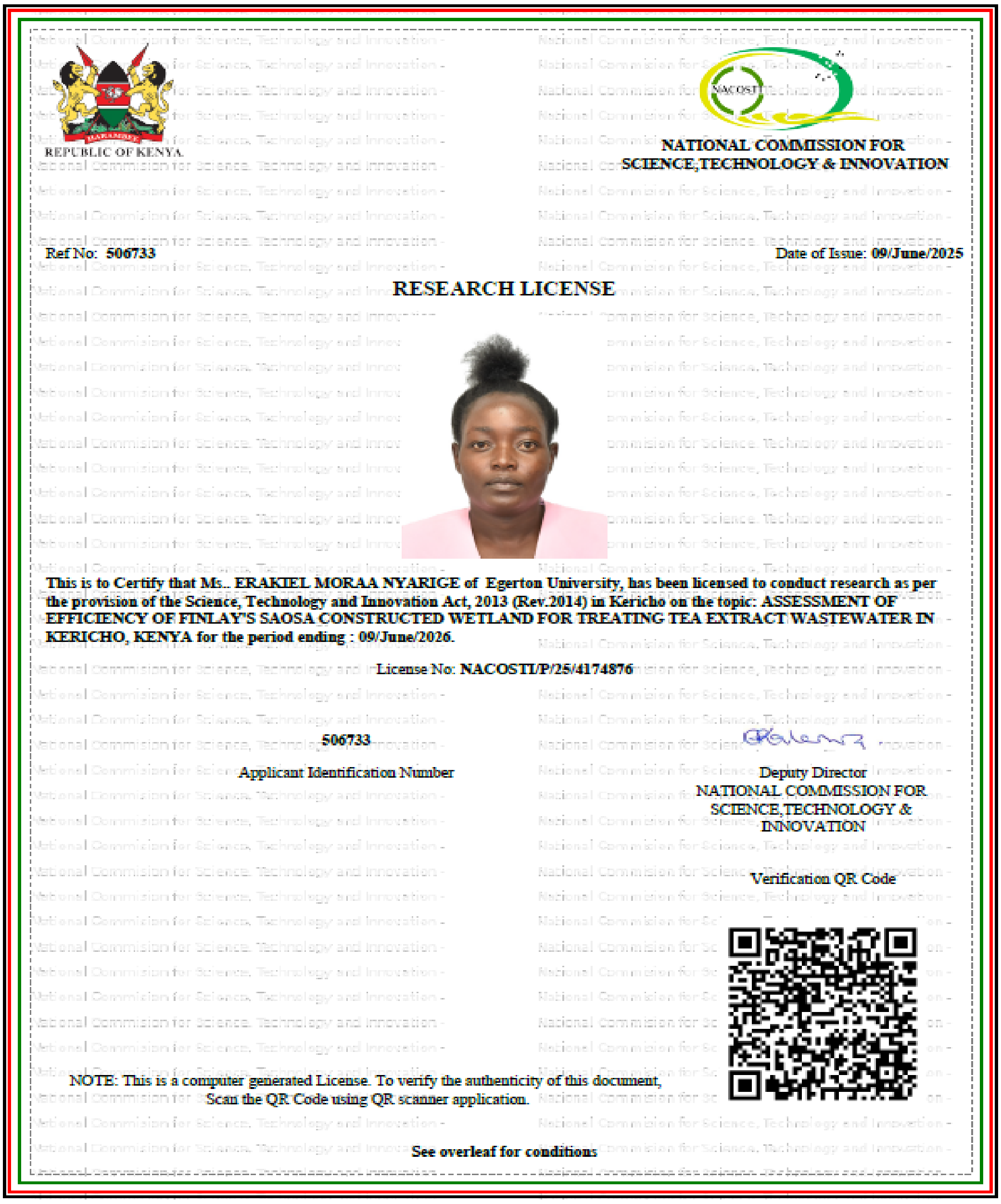
Yours sincerely.

Date. 27/05/2025

Prof. Kennedy N. Ondimu PhD
CHAIRMAN, EUISERC
LKK/BK/

"Transforming Lives through Quality Education"

Appendix E: Research permit granted by the National Commission for Science, Technology, and Innovation (NACOSTI) to conduct a study in Finlay Saosa



REPUBLIC OF KENYA

NATIONAL COMMISSION FOR SCIENCE,TECHNOLOGY & INNOVATION

Ref No: **506733**

Date of Issue: **09/June/2025**

RESEARCH LICENSE

This is to Certify that Ms.. ERAKIEL MORAA NYARIGE of Egerton University, has been licensed to conduct research as per the provision of the Science, Technology and Innovation Act, 2013 (Rev.2014) in Kericho on the topic: ASSESSMENT OF EFFICIENCY OF FINLAY'S SAOSA CONSTRUCTED WETLAND FOR TREATING TEA EXTRACT WASTEWATER IN KERICHO, KENYA for the period ending : 09/June/2026.

License No: **NACOSTI/P/25/4174876**

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Applicant Identification Number

Deputy Director
NATIONAL COMMISSION FOR
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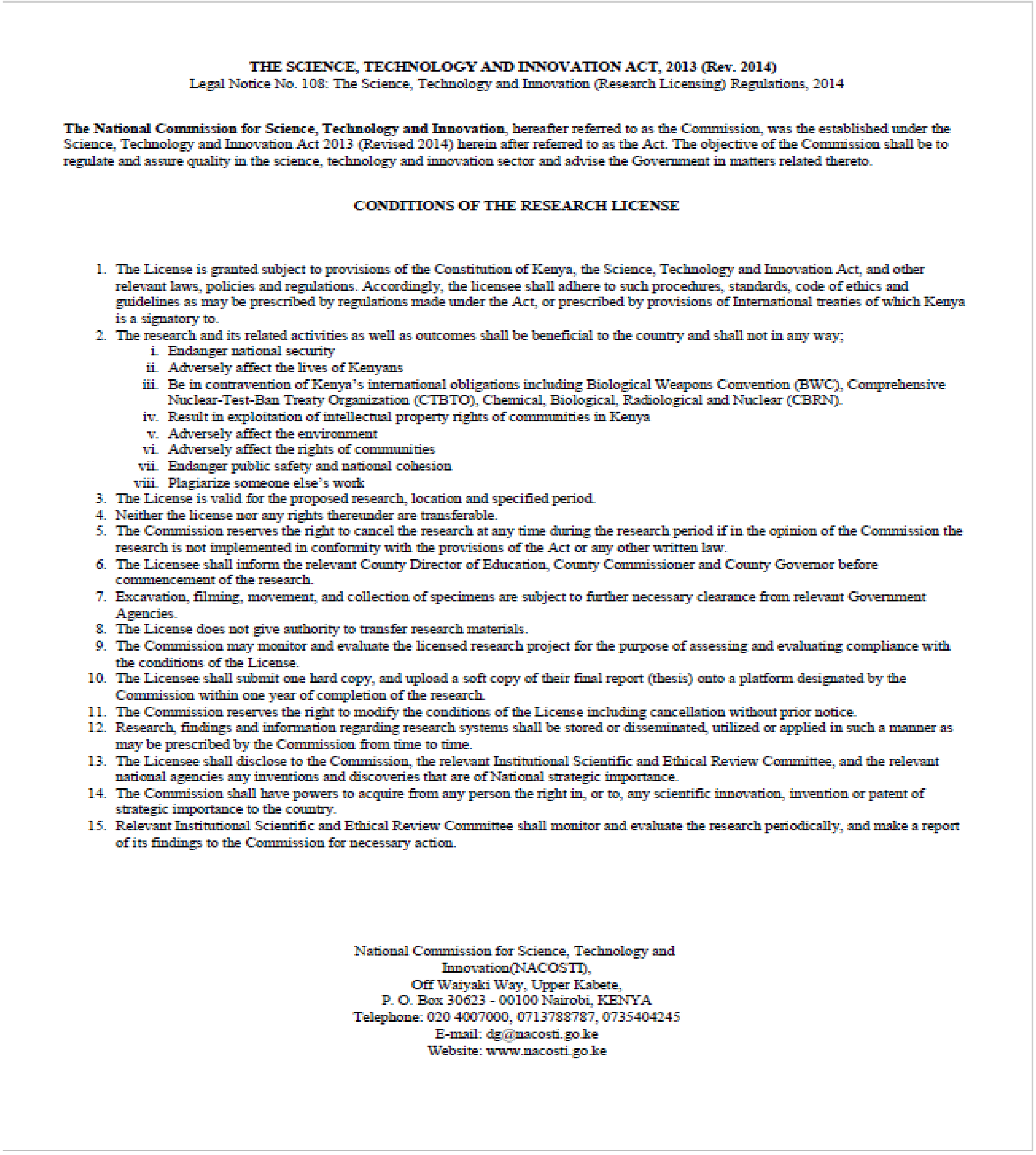

THE SCIENCE, TECHNOLOGY AND INNOVATION ACT, 2013 (Rev. 2014)

Legal Notice No. 108: The Science, Technology and Innovation (Research Licensing) Regulations, 2014

The National Commission for Science, Technology and Innovation, hereafter referred to as the Commission, was the established under the Science, Technology and Innovation Act 2013 (Revised 2014) herein after referred to as the Act. The objective of the Commission shall be to regulate and assure quality in the science, technology and innovation sector and advise the Government in matters related thereto.

CONDITIONS OF THE RESEARCH LICENSE

1. The License is granted subject to provisions of the Constitution of Kenya, the Science, Technology and Innovation Act, and other relevant laws, policies and regulations. Accordingly, the licensee shall adhere to such procedures, standards, code of ethics and guidelines as may be prescribed by regulations made under the Act, or prescribed by provisions of International treaties of which Kenya is a signatory to.
2. The research and its related activities as well as outcomes shall be beneficial to the country and shall not in any way;
    i. Endanger national security
    ii. Adversely affect the lives of Kenyans
    iii. Be in contravention of Kenya's international obligations including Biological Weapons Convention (BWC), Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), Chemical, Biological, Radiological and Nuclear (CBRN).
    iv. Result in exploitation of intellectual property rights of communities in Kenya
    v. Adversely affect the environment
    vi. Adversely affect the rights of communities
    vii. Endanger public safety and national cohesion
    viii. Plagiarize someone else's work
3. The License is valid for the proposed research, location and specified period.
4. Neither the license nor any rights thereunder are transferable.
5. The Commission reserves the right to cancel the research at any time during the research period if in the opinion of the Commission the research is not implemented in conformity with the provisions of the Act or any other written law.
6. The Licensee shall inform the relevant County Director of Education, County Commissioner and County Governor before commencement of the research.
7. Excavation, filming, movement, and collection of specimens are subject to further necessary clearance from relevant Government Agencies.
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11. The Commission reserves the right to modify the conditions of the License including cancellation without prior notice.
12. Research, findings and information regarding research systems shall be stored or disseminated, utilized or applied in such a manner as may be prescribed by the Commission from time to time.
13. The Licensee shall disclose to the Commission, the relevant Institutional Scientific and Ethical Review Committee, and the relevant national agencies any inventions and discoveries that are of National strategic importance.
14. The Commission shall have powers to acquire from any person the right in, or to, any scientific innovation, invention or patent of strategic importance to the country.
15. Relevant Institutional Scientific and Ethical Review Committee shall monitor and evaluate the research periodically, and make a report of its findings to the Commission for necessary action.

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