ACADEMICIA: An International Multidisciplinary Research Journal
ISSN: 2249-7137 Vol. 16 Issue 5, May, 2026 SJIF 2022= 8.252
A peer reviewed journal

CONSTRUCTED WETLANDS FOR WASTEWATER REUSE AND RENEWABLE-ENERGY-DRIVEN IRRIGATION IN TRINIDAD AND TOBAGO, WEST INDIES

Michelle Shah*; Hazi Azamathulla; Kiran Tota-Maharaj*****

*Ph.D. Research Scholar,
Director,
Water, Energy and Environmental Engineering (WEEE) Research Cluster,
Royal Agricultural University, Cirencester, Gloucestershire GL7 6JS, United Kingdom.
Land and Water Development Division,
Ministry of Agriculture and Fisheries,
Centeno, Trinidad and Tobago, West Indies.
Email Id: Michelle.Shah@student.rau.ac.uk

**Professor of Civil & Environmental Engineering,
The University of the West Indies,
St. Augustine Campus, Trinidad and Tobago, West Indies.
Email Id: hazi.azamathulla@sta.uwi.edu

***Professor & Chair,
Water Resources Management & Infrastructure,
Royal Agricultural University,
Cirencester, Gloucestershire GL7 6JS, United Kingdom.
Email Id: Kiran.Tota-Maharaj@rau.ac.uk

DOI: 10.5958/2249-7137.2026.00024.6

ABSTRACT

Constructed Wetlands are engineered systems designed to imitate natural wetlands for wastewater treatment. They utilise soil, plants and microbes to filter out pollutants and use macrophytes to absorb nutrients. This study adopts a mixed-methods research design to evaluate pollutant removal efficiencies and wastewater reuse potential using integrated nature-based solutions (NbS) and renewable energy solutions. Removal of key water quality parameters (BOD_5, COD, TSS, NH_4-N, PO_4^{3-} and E. coli*) was assessed by varying geotextile membrane types and biofilter media in experimental treatment rigs. Treatment performance was compared for reclaimed water (RW), conventional irrigation water (CW), and secondary effluent (SW) using a Wastewater Reuse (WWR) prototype. Horizontal flow constructed wetlands planted with* Phragmites australis *was designed with a cross-sectional area of 3.75 m^2, hydraulic loading rate of 0.8 $m^3\,m^{-2}\,day^{-1}$, and flow rate of 3 $m^3\,day^{-1}$, operating at retention times of 24–120 h. Field trials achieved average removal efficiencies of 75.99% (BOD), 76.16% (COD), 57.34% (TDS), 62.08% (nitrate), 58.03% (phosphate), and 57.83% (potassium). The study further evaluated a solar-powered automated drip irrigation system to quantify water savings, energy consumption, and crop yield outcomes. Knowledge, Attitudes, Practices, and Willingness to Pay were assessed to inform national wastewater reuse standards, supporting sustainable Water-Energy-Food-Ecosystems nexus.*

KEYWORDS: *Wastewater Reuse; Constructed Wetlands; Geotextiles; Solar-Powered Irrigation; Water Quality; WEFE Nexus.*

1.INTRODUCTION

This study aimed to investigate the risks and hazards associated with treated wastewater and agrochemicals, and to assess water quality for irrigation and crop quality at the proposed site for the Orange Grove Food Crop Project in Tacarigua, Trinidad and Tobago, West Indies, which is adjacent to the Trincity municipal wastewater treatment plant (WWTP) (see Figure 1).

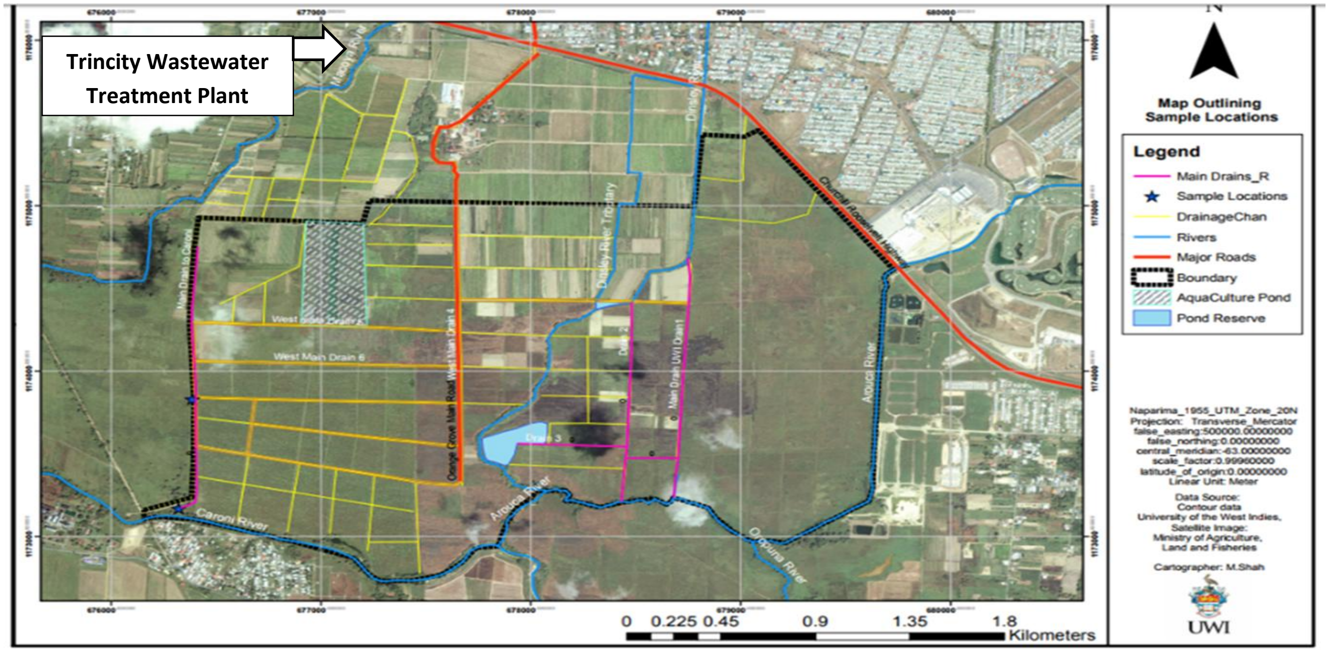

Figure 1.Map of Orange Grove Food Crop Project located near the Trincity Wastewater Treatment Plant, Trinidad and Tobago, West Indies.

1.1 AIM OF THE STUDY

The overarching aim of this study is to evaluate integrated nature-based and technological solutions for safe wastewater reuse in agriculture by assessing pollutant removal performance, irrigation efficiency, and resource recovery within constructed wetland and solar-powered irrigation systems.

1.2 SPECIFIC OBJECTIVES

To achieve this aim, the research study pursues the following specific objectives:

- To quantify the removal efficiencies of key water quality parameters (including BOD_5, COD, TSS, NH_4-N, PO_4^{3-}, and E. coli) by assessing the influence of different geotextile membrane types and biofilter media configurations in experimental biofilter rigs treating reclaimed water (RW), conventional irrigation water (CW), and secondary effluent (SW).
- To evaluate the treatment performance and hydraulic behaviour of vertical flow constructed wetland (VFCW) systems, comparing alternative configurations in terms of media

composition, depth, and vegetation, to identify cost-effective designs suitable for decentralised domestic wastewater treatment and potential reuse in irrigation.

- To assess the effectiveness of a solar-powered automated drip irrigation (SPADI) system, by quantifying water savings, energy consumption (kWh/day), and crop yield responses (biomass, marketable yield, and water use efficiency) for lettuce and kale under controlled experimental conditions.

The project site, the Orange Grove Food Crop Project, located in Trinidad, West Indies, offers a semi-controlled environment with a uniform soil type. This allows for experimental assessments, ensuring that produce will not enter the market until it is confirmed safe for consumption. Additionally, the site is prepared for equipment installation, including demonstration plots equipped with monitoring components, and has baseline soil property information available.

Lettuce (Lactucasativa) and kale (Brassica oleracea var. acephala) have been selected as the crop for this study due to its sensitivity to irrigation water quality issues. As the most commonly consumed raw vegetable, lettuce has a leafy structure that may protect pathogens from light and desiccation, promoting their persistence (Petterson et al., 2001). The choice of this crop was also influenced by its growth rate, given that the total data collection timeline was 18 months.

This study will examine the water-energy-food-ecosystems (WEFE) nexus, highlighting the connections between crop production risks, renewable energy, and the reuse of treated wastewater in agriculture. It aims to identify research gaps related to emerging pollutants that are insufficiently addressed in current regulations. Furthermore, it will assess how findings related to permeable geotextile membranes and filter materials (biochar and chitosan) could influence future wastewater management practices and explore the potential implications of these findings for policymakers in integrating agricultural practices with renewable energy solutions.

2. REVIEW OF LITERATURE

Agricultural use of reclaimed municipal wastewater has become a notable and economically viable alternative water resource (Drechsel et al., 2015; Eslamian, 2016). This practice is implemented on about 20 million of the 200 million hectares of globally irrigated land (Jaramillo &Restrepo, 2017), positioning agriculture as the largest user of reclaimed water (Lazarova et al., 2013) and a sector exhibiting significant economic benefits (Younos&Parece, 2016). The application of reclaimed water for crop irrigation presents multiple advantages, including mitigating stress on freshwater resources (Eslamian, 2016; Parsons et al., 2010), providing nutrients that minimize the need for synthetic fertilizers (Lyu et al., 2016; Pedrero et al., 2013b; Vicente-Sanchez et al., 2014; Vivaldi et al., 2015), and generating higher crop yields compared to freshwater irrigation (Vergine et al., 2016; Vivaldi et al., 2015). However, improper management of water reclamation can lead to negative consequences for the environment and human health (Eslamian, 2016; Lazarova et al., 2013). The most widely recognized risk is the potential introduction of pathogens into the food supply chain (Castro Ibanez et al., 2015; Lopez-Galvez et al., 2016b). Furthermore, increased salinity can adversely affect crops and soil quality (Pedrero et al., 2008; Pedrero et al., 2010), while phytotoxic elements can inhibit plant growth and reduce crop yields (Parsons et al., 2010; Pedrero, 2010). High levels of sodicity can also deteriorate soil structure (Pedrero& Asano, 2008; Pedrero et al., 2010). Contaminant removal is achieved through various processes: Sorption, where contaminants adhere to soil particles and organic matter; Biodegradation, in which microorganisms decompose organic contaminants into less harmful compounds; Phytoremediation, where plants absorb and accumulate contaminants or aid in their breakdown through root exudates; Photodegradation, which involves the breakdown of certain contaminants through light-induced chemical reactions; and Volatilization, where some contaminants transfer from water to air through evaporation.

3 METHODOLOGY

WWR-Prototype Design Experimental Setup

The research methodology incorporates Caribbean case studies and employs a mixed-methods approach with both quantitative and qualitative techniques. Two experimental setups, the constructed vertical flow wetland and gravity biofilter systems, will be tested with the selected crops. Three types of influent water will be utilized: reclaimed water (RW) from the WWR prototype, conventional irrigation water (CW), and secondary effluent (SW) from the Trincity wastewater treatment plant (WWTP), with RW produced by treating SW.The WWR prototype comprised three experimental reclaimed wastewater storage tanks/pipes, with one dedicated to reclaimed wastewater and engineered layers of granular material and geotextile membranes designed to collect treated wastewater. The laboratory setup enabled flow and water-quality measurements (see Figure 2). The three storage tanks/pipes were used to evaluate the water quality of the inflow (SW) and outflow (RW). The designs varied as follows: (i) without a geotextile membrane, (ii) with an upper geotextile membrane, and (iii) with both upper and lower geotextile membranes. Weekly monitoring of water quality parameters, including nutrients, biochemical oxygen demand, chemical oxygen demand, and suspended solids, was conducted to determine removal efficiencies (see Tables 1 and 2).

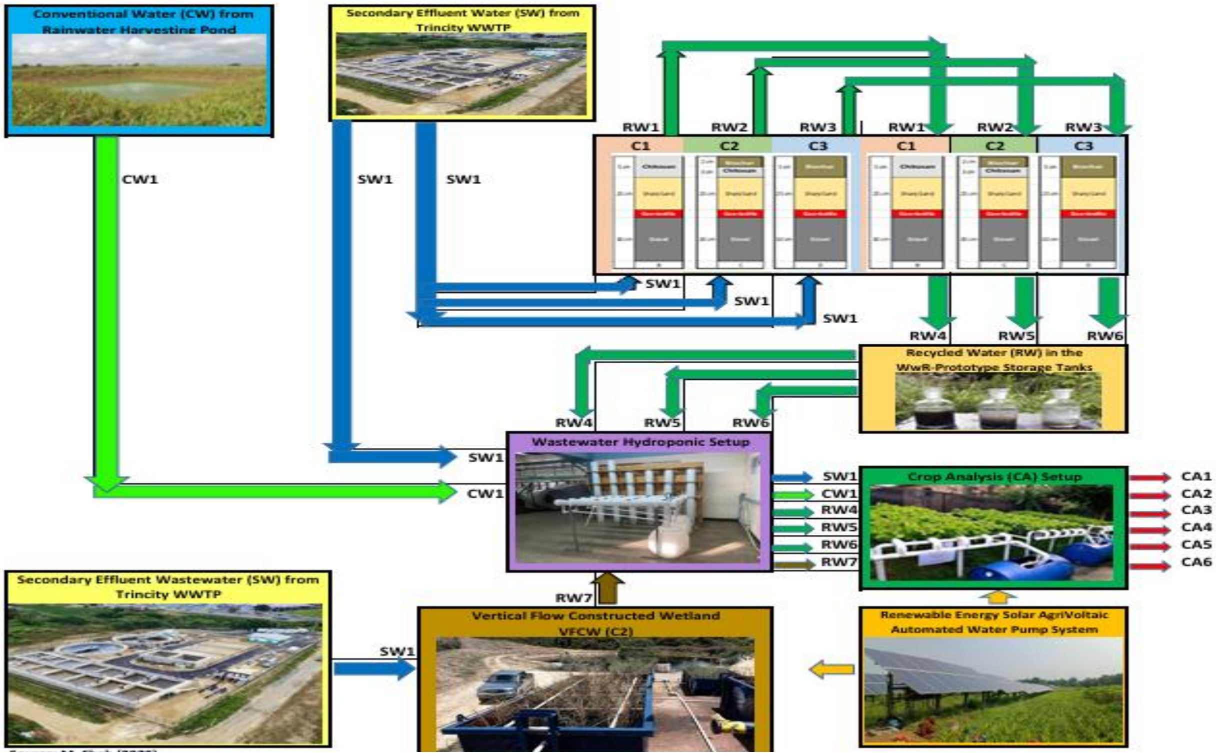

Figure 2. Flow Chart of Experimental Setup and Methodology at the University of the West Indies, St. Augustine Campus, Trinidad and Tobago

Experiments aimed to evaluate contaminant retention and the effectiveness of geotextile membranes and filters. The results would demonstrate the system's efficiency in removing contaminants from secondary effluent. The WWR-Prototype incorporates a permeable geotextile membrane and utilizes a combination of water treatment technologies, including biochar, chitosan, and gravel. Chitosan, derived from chitin found in marine organisms and fungi, along with biochar from biomass pyrolysis, enhances contaminant removal through sorption of heavy metals.

The geotextile membrane and bio-filter media systems were constructed using plastic water tanks/pipes with dimensions of 350 mm × 350 mm × 780 mm (length × width × depth). Geotextile membranes, which are porous fabrics used in agriculture, were fabricated using natural materials, such as jute and coir. They are eco-friendly, biodegradable, and sustainable.

3.1 Crop Experimental Setup

The cultivation of lettuce (Lactucasativa) and Kale (Brassica oleracea var. acephala) is scheduled to occur over a 90-day period spanning from January to March 2025. This will take place in 72.0 m² grow boxes situated adjacent to municipal wastewater treatment plant (WWTP) facilities in Orange Grove, Tacarigua. The project site coordinates were 10.63678° N (10° 38' 12″ N) latitude and -61.37686° W (61° 22' 37″ W) longitude. Lettuce and kale were selected for this study because of their pronounced susceptibility to salinity stress, which substantially influences growth patterns and nutritional content (Kim et al., 2008). Moreover, as raw vegetables are the most frequently consumed, lettuce is an excellent model for assessing safe agricultural production practices. The leafy structure of lettuce and kale may offer protection against pathogens by shielding them from light exposure and desiccation, potentially facilitating their continued survival (Petterson et al., 2001).

3.2 Irrigation Water Sources and Methods

The irrigation process utilised three water types: i) reclaimed water (RW) from the WWR prototype, using secondary effluent from a wastewater treatment plant, ii) conventional irrigation water (CW), and iii) secondary effluent (SW) from the Trincity WWTP. RW was produced by processing SW using a WWR prototype. CW, supplied by the Orange Grove irrigation community, is a blend of various sources: the Caroni River (88.7%), Macoya River (3.0%), Dinsley River (6.7%), and Tantrill River (1.6%). CW is mainly used for agronomic quality control owing to its suitable salinity levels. SW was obtained from the Trincity WWTP after undergoing treatment involving pretreatment steps, double-stage activated sludge with extended aeration, and secondary clarification. The experiment combined three water types (RW, CW, and SW) with two types of leafy vegetable crops, namely lettuce and kale (L and K), resulting in six treatments: RW-L, RW-K, CW-L, CW-K, SW-L, and SW-SK, each with four lettuce and kale plant replicates. Using a randomized design, 144 lettuce and kale plants were planted per treatment plot (12 plants/m² spacing) on ridges, totalling 864 lettuce and kale plants in the entire area.

3.3 Irrigation Water Quality Analysis

Physicochemical analyses were conducted for different irrigation water types. Bi-weekly grab samples (eight in total) were collected during the experimental period using clean, non-sterile bottles (not for microbiological analyses). The bottles were rinsed and filled with water before collection from the various sites. After transportation to the laboratory, samples were stored at

Five Degrees Celsius prior to processing. A closed hydroponic system was set up, which saved more water and fertilizers than an open system. The three types of water used were conventional water (CW), secondary water/treated wastewater from the water treatment plant (SW), and recycled treated wastewater (RW). These waters were pumped through the growing zone to flow over the lettuce plant roots. The water-saving effect of this system has been confirmed by many studies. A potential problem of the closed hydroponic system is the accumulation of salt ions, mainly sodium (Na) and chlorine (Cl). Increased salt concentration can lead to decreased plant photosynthesis and transpiration rates. Elevated salt levels may cause a reduction in plant weight and apparent toxicity effects caused by chlorine (Cl).

Wastewater quality parameters measured included, physicochemical parameters such as pH, Conductivity, Total Dissolved Solids (TDS), Dissolved Oxygen (DO) and Temperature. Chemical parameters measured were Nitrate, Ammonia, Phosphorus, Potassium, Chloride and COD. The bacteriological parameter measured was faecal coliform.

These parameters were selected based on their importance in wastewater treatment and reuse for irrigation. Temperature and pH help to understand the operating conditions of the system. TDS, Conductivity, and DO provide the primary indications of the chemical constituents in wastewater. Nitrates, potassium, and phosphorus are essential nutrients for crop growth. This study aimed to determine the availability of chemical parameters in the final effluent. Ammonia was measured because of its toxic nature, which can affect biological life and treatment system performance at high levels. Chemical oxygen demand was measured to quantify organic loading, as high organic content depletes oxygen in the receiving environment. COD measures the total amount of oxygen needed to break down both organic and inorganic matter in water. BOD was measured to quantify the amount of oxygen. BOD measures the amount of oxygen that microorganisms need to break down organic matter in water. It is desirable that the final effluent has low organic loading. Faecal coliform was used as an indicator of faecal pollution, representing the level of biological pollution loading (see Figure 3).

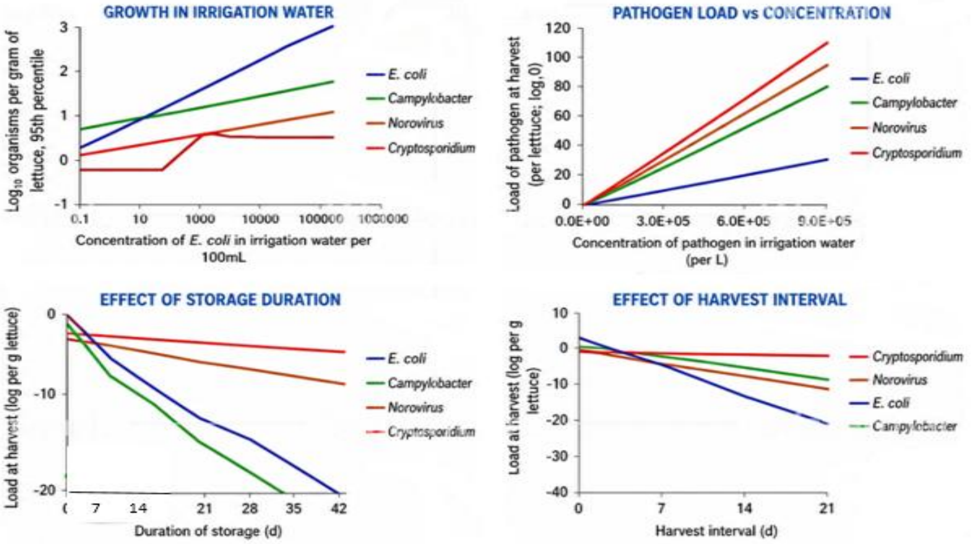

Figure 3. Graphs (i) to (iv) Showing Modelled Pathogen Survival Rates in Water and on Vegetables(Adapted from Pond, K. et al. (2007), B17005 Review of the Use of Water in UK Agriculture)

3.4 Agronomic/ Crop Quality Analyses (Lettuce and Kale)

For analysing agronomic quality, microbial analyses are performed whereby sampling of lettuces and kale are performed at their growth stage 49, according to the BBCH scale (Meier, 2001), when the produce reaches commercial size. Each sample consisted of a whole lettuce/kale head cut from its base, with soil removed. Fresh (whole lettuce/kale) and commercial (cleaned lettuce/kale, without outer leaves) weights were measured on-site immediately after harvesting and drying the lettuce with paper towels to avoid inaccuracies due to plant water losses and external moisture. Lettuces/kale were dried for at least two days at 65 °C to measure dry weight. The percentage of water content in lettuces/kale was calculated based on fresh and dry weight values. To analyse C concentrations, macronutrients (total N, NO_3^-, PO_4^{3-}, K, Ca, Mg), micronutrients, phytotoxic elements (B, Cl^-, Na), and metals, lettuce leaves underwent a cleaning preparation process. This process consisted of detergent washing (Alconox 0.1%), rinsing with tap water, cleaning with 0.005% hydrogen chloride (HCl) solution, and rinsing with distilled water. Cleaned samples were then drained by leaving them on filter paper. Subsequently, they were oven-dried at 65 °C for at least two days. Dried samples were blended and digested in nitric perchloric acid (2:1).

(i) Field sampling: Collect soil and plant samples from different parts of the field.

(ii) Laboratory analysis: Analyse soil for nutrient content, pH, organic matter, and other properties.

(iii) Plant analysis: Assess plant health, growth parameters, and yield.

(iv) Pest and disease assessment: Check for signs of pests and diseases.

(v) Data Interpretation: Use agronomic data to make decisions on fertilization, irrigation, and pest control.

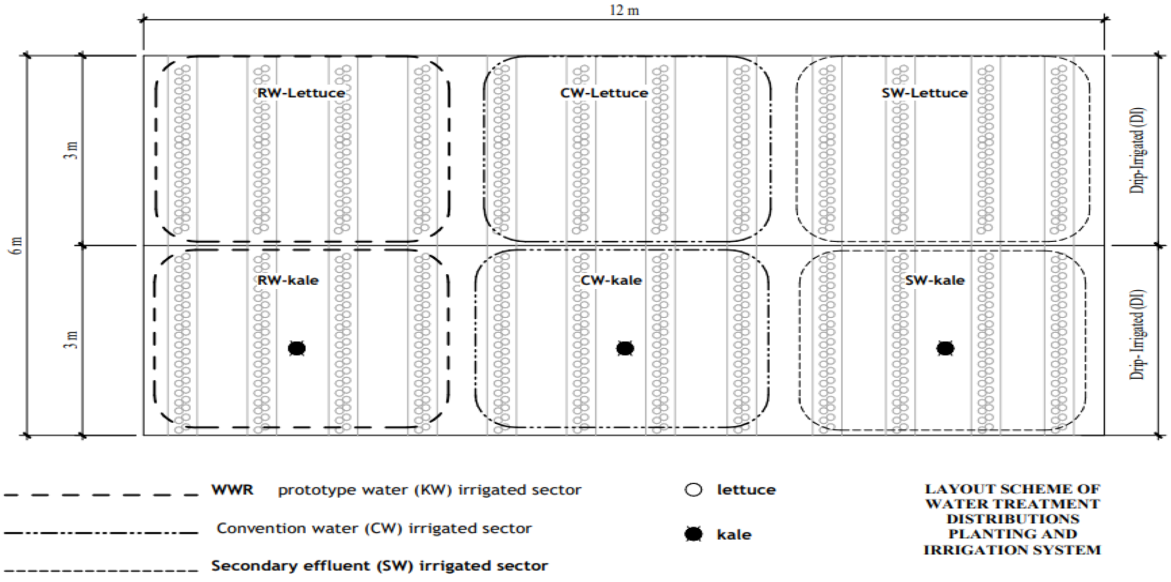

Figure 4. Schematic Layout of Planting and Irrigation Distribution Layout in the Field

3.5 Vertical Flow Constructed Wetland System Experimental Setup

The vertical flow-constructed wetland system experimental setup wetlands tested two crop types (lettuce and kale) using three water sources: reclaimed water (RW), conventional irrigation water (CW), and secondary effluent (SW) from the Trincity Wastewater Treatment Plant, and is designed for a single household, has a surface area of 16 m^2 and a total depth of 1.4 m. It consists of a 0.2 m drainage layer, a 1.0 m filter sand layer, and a 0.2 m insulation layer, with a 0.2 m embankment to prevent water intrusion. The filter bed is enclosed by a 0.5 mm thick geotextile membrane protection, with common reed (P. Australis) planted at four (4) plants/m^2 using seedlings or rhizomes (See Figure 5).

A vertical flow constructed wetland (VFCW) is an engineered system that treats wastewater by filtering it through layers of sand, gravel, and other permeable materials, with the liquid collected at the base. VFCWs effectively treat agricultural wastewater by mimicking natural wetland processes through the use of vegetation, soil, and microbes. They utilize physical, biological, and chemical mechanisms to remove pollutants. VFCWs require proper lining and filter materials.

Design specifications of vertical flow constructed wetlands and design guidelines for efficient wastewater treatment

(i) Depth: 0.5 1 meter.

(ii) Surface area based on wastewater volume and treatment goals.

(iii) Flow rate: Ensure adequate contact time with the filter medium.

(iv) Plant selection: Use deep-rooted wetland plants to enhance permeability and microbial support.

(v) Maintenance access: Include access points for solid removal and vegetation management.

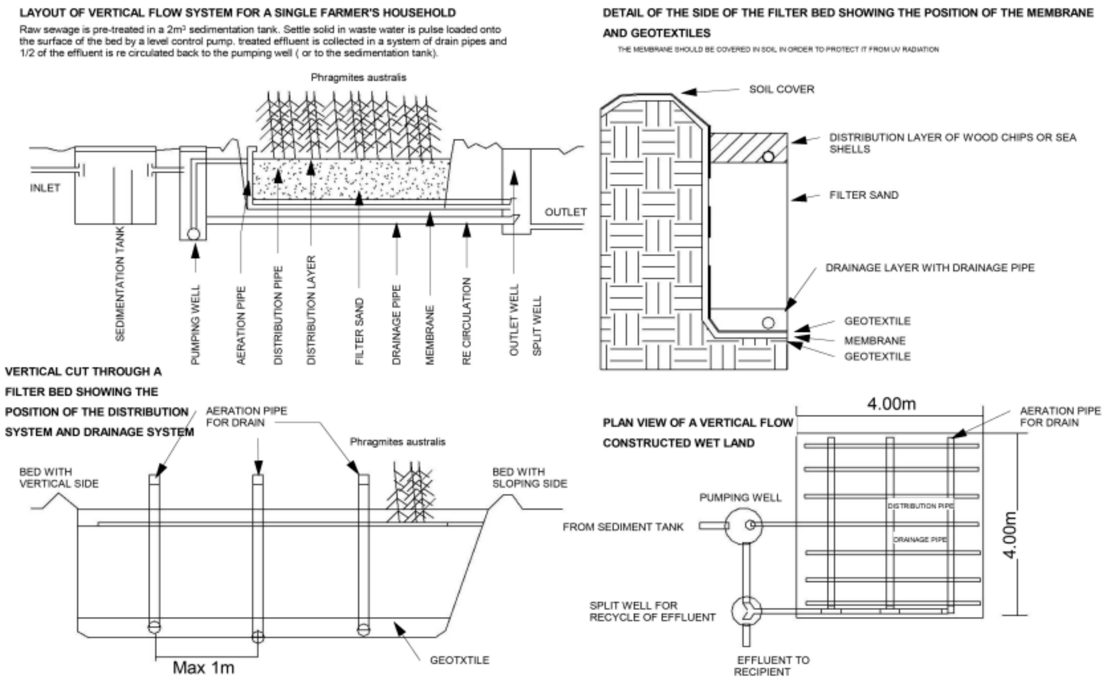

Figure 5. Schematic Diagram Showing Layout of Vertical Flow ConstructedWetland System

3.6 Horizontal Flow Constructed Wetland System Experimental Setup

A horizontal free-surface flow constructed wetland (HFCW) experimental setup (See Figure 6) was developed at the Fluids Laboratory, University of the West Indies, St. Augustine, Trinidad and Tobago, to treat greywater generated and collected from bathrooms, kitchens, and laundries of households within the Orange Grove, Tacarigua community. An HFSF wetland was chosen over vertical subsurface flow system because it requires less complex construction, allows direct plant growth on the water surface, and is more adaptable to fluctuating greywater loads in urban communities with limited resources (Alao et al., 2021; Raphael et al., 2023; Mustapha et al., 2018).

The HFCW wetland system for open-air conditions, shown in Figure 6, was constructed with dimensions of 12 m × 1 m × 1 m in length, width, and depth, respectively, in accordance with the recommended design ranges for horizontal flow constructed wetlands, which specify depths of 0.3–1.0 m and length-to-width ratios of 10:1 to 20:1 (Kadlec and Wallace, 2009; Vymazal, 2011). The system components comprised an inlet, a 1.5-m detention basin, and three treatment cells lined in sequence with an impermeable polymer to prevent seepage, and all were maintained under open-air conditions.

The HFSF was operated with three types of water CW, SW, and RW and a minimum hydraulic loading rate (HLR) of 0.20 m/day mg/L, which falls within the recommended design and operational ranges of 0.10–0.40 m/day for horizontal flow wetlands in warm climates (Arden and Ma, 2018; Rahman et al., 2023) and was selected to represent low-flow conditions for evaluating the influence of the hydraulic rate on the efficiency of pollutant removal.

Phragmites australis, which stands upright and is rooted, was used as the treatment vegetation because of its rapid growth, high nutrient uptake efficiency, tolerance to varying pollutant loads, and proven performance in tropical constructed wetlands for greywater treatment. It was then allowed to stabilize for three months before continuous operation for four months. To account for any potential environmental influence on the performance of the wetland, the ambient temperature and rainfall were recorded throughout the period of operation.

The effectiveness of treatment was evaluated by monitoring water quality parameters, including biochemical oxygen demand (BOD), total phosphorus, and total suspended solids. Sampling was performed following the procedures outlined by APHA, AWWA, and WEF (2012). The volumes of the influent and effluent were measured volumetrically every two to three days to calculate the average daily discharge for each unit in the system for a detailed performance analysis of the constructed wetland for the three wastewater types (CW, SW, and RW).

The field dimension of the constructed wetland was 250 x 150 x 80 cm with a slope of 0.01 (1 %). The wetland media consisted of a gravel bed underlain on an impermeable concrete surface. The bed was filled to a height of 50 cm with coarse rock, medium gravel, fine gravel, gravelly sand, and coarse sand. The top portion of the wetland unit was filled with local sandy clay loam soil to support vegetation. This process depicted in Figure 6.

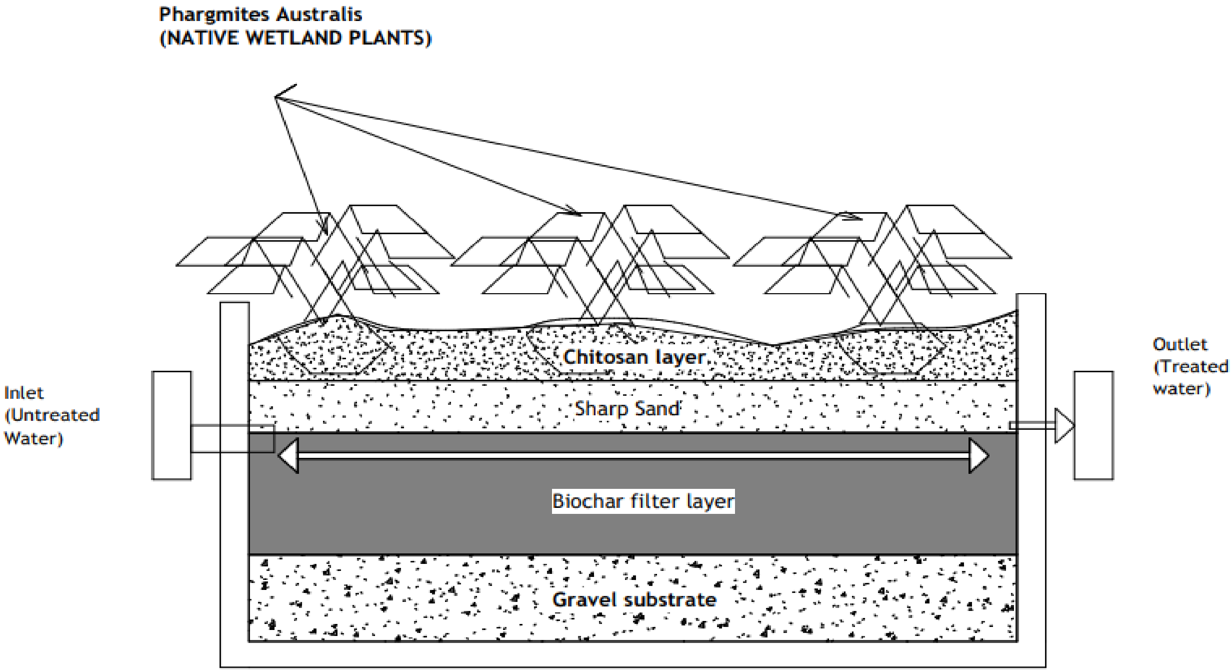

Figure 6. Experimental Setup of Horizontal (Cross) Flow Constructed Wetland System – Planted Horizontal Flow Constructed Wetland Setup

3.7 Sample Collection / Laboratory Testing

Samples were collected bi-weekly from the influent and effluent of the HFSF constructed wetland unit operated at each hydraulic loading rate. The collections were done by means of plastic containers that had been sterilized and rinsed with the greywater sample before use. These samples were collected for analysis after three months, to ensure the stability of the operation of the system. The concentrations of biochemical oxygen demand (BOD_5), total phosphate (TP), total suspended solids (TSS), and ammonium nitrogen (NH_4–N) were determined according to the Standard Methods for the Examination of Water and Wastewater (APHA, AWWA, and WEF, 2012), corresponding to Methods 5210 B, 4500-P, 2540 D, and 4500-NH3, respectively. All analyses were performed in triplicate (n = 3) to ensure the precision of measurements, as no replicate treatment units were constructed; temporal replication was achieved through repeated bi-weekly sampling during the study period. The influent and effluent wastewater flows were measured for each HFSF unit, enabling the calculation of the daily mean discharge. Pollutant mass loading and removal efficiency were subsequently estimated using the measured flow and concentration data.

3.8 Solar Powered Automated Pump System for Drip Irrigation

A solar-powered automated pump system for drip irrigation utilizing a pump and solar panels was employed to irrigate lettuce and kale crops. This system efficiently delivers water directly to plant roots, thereby minimizing water losses from evaporation and runoff. In addition to water conservation, it reduces reliance on non-renewable energy sources.

- Solar Power Calculated for Pumping
- Motor Power = 2.0 – 3.7 kW

The Solar PV Array is used for Irrigation purposes. This system delivers approximately 140 m3 of water per day from a total head of 10 m. Comparing this energy need with the theoretical Hydraulic Power, and assuming the pump works 8 hrs/day, and only 60% of the Peak Solar Power utilized, then

$$P \text{ hydraulic} = \frac{140 \text{ x } 0.6}{8 \text{ x } 3600} (10 \text{ x } 1000 \text{ x } 9.81) = 286 \text{ W}$$

Supply and installation of a 3.0 kW solar photovoltaic (PV) panel (monocrystalline) system array. Installation requires mounting and securing to metal structures on the ground of adequate strength and design to withstand the load of modules and high wind velocities of up to 150 km/h. Provision of a 6 kW pure sine wave inverter and a 6 kW solar hybrid system split-phase 120 V/ 240 V, 60 Hz, 5.1 kW lithium-ion battery bank controller system (deep-cycle lead acid [AGM] type with an appropriate 12 V battery system rating). The use of solar power ensures a sustainable and cost-effective irrigation method, which is crucial for regions experiencing water scarcity owing to climate change.

3.9 Rule of Thumb for Solar Water Pumping

A common rule of thumb is that a 1000 Wp (1 kWp) solar water pump can draw and pump approximately 40 m^3 of water per day from a source that is up to 10 m deep. We find that the hydraulic energy is 1.09 kWh per day. Assuming eight hours of sunshine, 80% motor-pump efficiency, and 10% pipe loss, the required electric power would be 0.19 kW. In other words, a large safety margin is assumed. Typically, 40 m^3 of water per day is sufficient to irrigate up to one hectare of land planted with regular crops.

The aim was to find an affordable pump and minimize costs by avoiding the use of batteries. The use of a DC pump avoided the cost of DC/AC conversion. The drawback is that DC motors have a shorter life than AC motors. Marine pumps were found to be a good choice; however, many were designed only for low heads. The actual pump can deliver approximately 15 m^3/h or 4 L/s at zero head. It can operate at a head of 5–6 m; however, the flow rate is lower, although sufficient for the purpose. In this case, the motor was assumed to have a life of approximately one year. However, the profit from irrigation could cover the cost of motor replacement. In total, the pumping system cost less than USD 1, 000. No electronic controllers were used; only a simple circuit breaker was used. The pump can irrigate approximately half a hectare (5000 m^2). A flow rate of 4 m^3/h for six hours will provide approximately 50 m^3/hectare/day.

3.10 Statistical Analysis

Statistical analysis of water and crop quality data was conducted using analysis of variance (ANOVA). Statistical Package for the Social Sciences (SPSS Version 19) was used to analyse the results. A combination of qualitative and quantitative data will be gathered from n respondents throughout Trinidad and Tobago using convenience sampling. The sample size, n, was determined using Kish'sformula. A KAP survey will be implemented to assess stakeholders' knowledge of treated wastewater, their attitudes towards its reuse, and current practices. The target population of the study consisted of 223 farmers. To achieve a 95% confidence level, Kish's formula was used to calculate the sample size, as described by Assaf and Al Hejji (2006). Based on this calculation, questionnaires were distributed to at least 59 farmers within the catchment area to maintain a 95% confidence level:

$n = n^{1} / [1 + (n^{1} / N)]$
where:

All Farmers (Registered/ Non-Registered)	
$n^1 = S^2/V^2 = (0.5)^2 /(0.06)^2 = 69.44$ N= 223 n = 69.44 / [1 + (69.44/ 223)] = 52.95	Allowing for the addition of a non-responsive rate of 5 to 15 % and using a 12% rate (Ameer, 2005; Amoako, 2011):12/100 * 52.95 = 6.35 = 6.0 Total Farmers, n = 53 + 6 = 59

N = Total number of population,

n = Sample size from a finite population,

n^1 = Sample size from infinite population = S^2/V^2

S = is the variance of the population elements, and V is the standard error of the sampling population (S=0.5, V=0.06).

Statistical analysis will also present gaps where innovation can be achieved. Wastewater reuse in the agricultural sector has economic benefits that can improve farmers' livelihoods. Jiménez et al. (2011) reported a doubling of revenue with wastewater reuse in the sector. Michetti et al. (2019) warned that dissonance between demand and supply affects expenditure and market stability.

3.10.1 Statistical Analysis using t Tests

Table 1 shows the BOD, COD, Total dissolved solids, Nitrate, Phosphate, and Potassium value comparison of raw and treated wastewater analysis using t test. The table shows comparison of mean, Standard deviation, Standard error mean. The two-tailed P value equals 0.0029. By conventional criteria, this difference is considered to be very statistically significant. The mean of raw water minus treated water equals 124.60. 95 % confidence interval is obtained with difference from 55.12 to 194.08. Intermediate values used in calculations were t = 4.0569, df = 9, and standard error of difference = 30.713. The two-tailed P value for COD comparison equals 0.0011. By conventional criteria, this difference is considered to be very statistically significant. The mean of raw water minus treated water equals 228.280. 95 % confidence interval of this difference: From 119.345 to 337.215 intermediate values used in calculations are t = 4.7405, df = 9, and standard error of difference = 48.156 (Table 2). The two-tailed P value for TDS is less than 0.0001. By conventional criteria, this difference is considered to be extremely statistically significant. The mean of raw water minus treated water equals 603.33. 95 % confidence interval of this difference is from 488.90 to 717.77. Intermediate values used in calculations are t = 11.7473, df = 10, and standard error of difference = 51.359.

The two-tailed P value for nitrate equals 0.0003. By conventional criteria, this difference is considered to be extremely statistically significant. The mean of raw water minus treated water equals 16.17. 95 % confidence interval is obtained with a difference from 9.66 to 22.67. Intermediate values used in calculations are t = 5.6239, df = 9, and standard error of difference = 2.875. The two-tailed P value for phosphate equals 0.0767. By conventional criteria, this difference is considered to be not quite statistically significant. The mean of raw water minus treated water equals 3.1863. 95 % confidence interval is obtained of difference from -0.4202 to 6.7929. Intermediate values used in calculations are t = 1.9986, df = 9, and standard error of difference = 1.594. The two-tailed P value for Potassium equals 0.0023. By conventional criteria, this difference is considered to be very statistically significant. The mean of raw water minus treated water equals 6.5917. 95 % confidence interval of difference from 3.0554 to 10.1280 is obtained. Intermediate values used in calculations: t = 4.2167, df = 9, and standard error of difference = 1.563.

After t test analysis, it was observed that every parameter before and after treatment is showing a 95 % confidence interval which means the constructed wetland is showing higher removal efficiency for all the selected parameters. Nitrification and denitrification are the main processes for nitrogen removal from wastewater. Denitrification is an anaerobic heterotrophic microbial process often limited by the presence of oxygen (O2) and the availability of labile carbon substrates. Nitrification is an aerobic chemoautotrophic process (Ong et al. 2011). The major processes responsible for phosphorus removal in SFWC are typically by adsorption, precipitation, and plant up-take rates. The frequent filtration materials used in SFCW are gravel, which is commonly good in absorption compared to the plant roots (Vymazal 2004). Phosphorus is an important nutrient required for plant growth and is usually act as a limiting factor for vegetative productivity. Phosphorus is transformed in the wetland by a complicated biogeochemical cycle. Accordingly, most of the researchers claimed that wetlands are not efficient in phosphorus reduction (Kadlec and Knight 1996; Adeniran et al. 2012; Akratos et al. 2008).

Table 1. BOD, COD, and TDS value comparison using t test

SI. No.	Group	BOD		COD		TDS	
		Raw	Treated	Raw	Treated	Raw	Treated
1	Mean	155.00	30.40	287.600	59.320	1050.00	446.67
2	Standard Deviation (SD)	68.02	2.19	106.516	6.922	118.32	42.74
3	SEM	27.77	0.98	43.485	3.096	48.30	17.45
4	N	6	5	6	5	6	6

Table 2. Nitrate, Phosphate, and Potassium Value comparison using t test

SI. No.	Group	Nitrate		Phosphate		Potassium	
		Raw	Treated	Raw	Treated	Raw	Treated
1	Mean	30.17	14.00	6.0183	2.8320	12.1917	5.6000
2	Standard Deviation (SD)	5.64	3.32	3.1317	1.8271	2.9665	1.9987
3	SEM	2.30	1.48	1.2785	0.8171	1.2111	0.8939
4	N	6	5	6	5	6	5

4. REVIEW FINDINGS

Irrigation Water

The water reclamation system of the WWR prototype was expected to exhibit removal efficiencies for EC, SAR, turbidity, and TSS. Removal efficiencies for nutrients of agronomic interest, i.e. The removal efficiency for $PO_4{}^{3-}$ concentration was analysed. Removal efficiency for $PO_4{}^{3-}$ concentration will be analysed. The removal efficiency of E. coli is expected to be obtained. Concentrations of other metals and metalloids were determined whether under or over the detection limit. The presence of culturable E. coli will be assessed for significant differences amongst the different types of irrigation water. In this regard, storage and conveyance of CW through open-air reservoirs and canals, respectively, renders this water source prone to contamination before reaching the end user. In this regard, storage and conveyance of CW through open-air reservoirs and canals, respectively, render this water source prone to contamination before reaching the end user.

Table 3. Expected Results for Wastewater Quality

WATER QUALITY VARIABLE	**UNITS**	**EXPECTED RESULTS**	**NO RESTRICTION FOR IRRIGATION**	**SEVERE RESTRICTION FOR IRRIGATION**
Faecal Coliform	Count/ 100 ml		-	< 1000
Nitrate-N	mg/L	<5	< 5	>30
Nitrogen (NO3-N)	mg/L	<5	<5	
pH	-	7.42	6.5 – 8.4	<6.5 &>8.4
Electrical Conductivity	mmho/cm	<0.7	< 0.7	>3.0
Total Dissolved Solids	mg/L	<450	450	>2,000
Total Suspended Solids	mg/L	NIL	NIL	>100
Sodium (Na)	SAR	<3		
Boron (B)	mg/L	<0.7	0.7	3.0
Chloride (Cl)	mg/L	<4	3.0	40.0
Turbidity	NTU		< 2 - 5	-
Dissolved Oxygen	mg/L		2 - 4	-
Biological Oxygen Demand(BOD), 5 days @ 27 deg. C	mg/L	2.64	10 - 30	30
Chemical Oxygen Demand (COD)	mg/L	7.2		250
Temperature	Deg. C		20 - 30	-
Oil and Grease	mg/L	2		10
Pesticides		≤ 0.01		
True Colour Units	TCU	1		5
Iron (Fe)	mg/L	NIL		3
Nickel (Ni)	mg/L	NIL		3
Chromium (Cr)	mg/L	NIL		2
Colony Forming Units (CFU) Bacteria		NIL		NIL
LC 50 (Bio Assay Test)		>96%		90%

4.1 Horizontal Flow Constructed Wetland System

Table 4. The Expected Results of a Performance Data (mean +1 S.D.) of Single House Horizontal Flow Constructed Wetland System for Water Catchment Area of 12,000 persons, and farming acreage of 355 acres.

System	**Parameter**	**Inlet**	**Outlet**	**Removal Efficiency (%)**
Horizontal Flow System (Without Circulation)	TSS BOD NH_4-N $NO_2 + NO_3$-N Total N Total P	85±28 254±123 105±45 <0.1 125±51 17.2±7.0	8±3 19±4 23±17 40±13 72±28 13.0±6.6	91 92 78 - 43 25
Horizontal Flow System (With 100% Recirculation)	TSS BOD NH4-N $NO_2 + NO_3$-N Total N Total P	68±22 100±35 45±13 0.13±0.00 57±13 5.2±1.7	3±1 11±3 7±1 36±4 44±5 5.7±1.2	96 89 85 - 23 0

NB: The inlet samples were collected as grab samples after the effluent water exits from the sump containing treated wastewater that meets the surface water quality regulations for rivers and water channels (WHO, 2011). This is for a water catchment area of 12,000 people and a farming acreage of 355 acres.

4.2 Influent Wastewater Characterization

The influent treated wastewater (SW) is characterized by Table 5.

Table 5: Properties of Influent Wastewater (SW)

SI. No.	**Parameter**	**Concentrations in mg/l**		
		Min	**Max**	**Mean**
1	Biological Oxygen Demand (BOD)	101	3390	643.2308
2	Chemical Oxygen Demand (COD)	315	1823	674.923
3	Total Nitrogen (TN)	2.28	196	60.37231
4	Total Phosphorous (TP)	0.06	32.6	14.01385

The parameters Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Nitrogen (TN) and Total Phosphorus (TP) were determined based on standard methods. The analysis was done immediately after sample collection, otherwise were properly stored. Low values of BOD, COD occur during heavy rainfall which indicates clear dilution effect.

4.3 Organics and Nutrient Removal in PAGS

The constructed wetland tank was filled with water for a period of one month until well establishment of the wetland plant species, PhragmiteAustalis. The treated wastewater (SW) was applied after one month. The systems were operated under four different hydraulic conditions by varying hydraulic residence time as 2, 4, 6 and 8 days (Table 6).

Table 6. Results of Pilot Scale Constructed Wetland Tank

Parameter	Outlet at Hydraulic Retention Time (HRT) at n Days							
	Inlet	2 Days	Inlet	4 Days	Inlet	6 Days	Inlet	8 Days
COD	174	105	176	98	179	64	161	49
BOD	48	34	42	33	39	22	36	16
TN	0.30	0.23	0.28	0.26	0.32	0.22	0.22	0.12
TP	2.25	1.68	2.22	1.59	2.27	1.38	2.19	2.19

The COD removal efficiencies were 39, 44, 64, and 69% for HRT of 2, 4, 6, 8 days, respectively. The BOD removal efficiencies were 29, 21, 43, and 56% for HRT of 2, 4, 6, 8 days, respectively. The TN removal efficiencies were 23, 7, 31, and 45% for HRT of 2, 4, 6, 8 days, respectively. The TP removal efficiencies were 25, 28, 39, and 75% for HRT of 2, 4, 6, 8 days, respectively.

As shown in Figure 8, there was a slight difference (5%) in removal between HRT of 2 days and 4 days. As the HRT increased to 6 days, there was 19% increase in COD removal when compared to COD removal at 4 days. The COD removal was doubled when there was an increase in HRT from 4 days to 8 days. BOD removal dynamics slightly differs from COD removal dynamics. There was 8% decrease in efficiency when HRT increased from 2 days to 4 days. The removal efficiency doubled at 6 days HRT and it further increased to 56% at 8 days HRT.

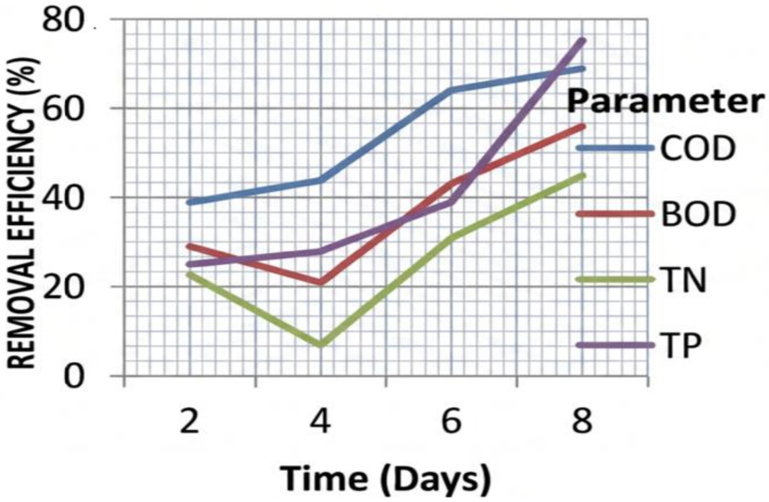

Figure 8. Organic and Nutrient Removal in Phragmitesaustralis HFCW(Adapted fromAbou-Elela, S. I., Golinelli, G., El-Tabl, A. S., &Hellal, M. S., 2014).

There was a two-thirds (2/3) decrease in TN removal efficiency when HRT increased from 2 days to 4 days and 1/3 increase at 6 days HRT. The TN removal efficiency further increased to 45% at 8 days HRT. There was only 3% increase in TP removal efficiency when there was an increase in HRT from 2 days to 4 days. And there was 11% increase at 6 days HRT compared to 4 days HRT. But the TP removal efficiency reached 75% at 8 days HRT.

Similar study to determine the effectiveness of constructed wetlands to treat tertiary effluent wastewater generated from studies involvingPaşaköy Advanced Biological Wastewater

Treatment Plant, Cecen, F. et al., (2011), showed that TP removal efficiency (60%) might be due to use of gravel substrate. TP removal rates increased when the HRT was prolonged. But, increasing HRT from 2 days to 4 days did not improve the efficiency in terms of N and P removal.

There was an increasing trend in COD removal efficiency as the HRT increased from 2 days to 6 days. Further increase in HRT to 8 days did not change the COD removal efficiency. There was an increasing trend in BOD removal efficiency as the HRT increased from 2 days to 8 days as it doubled from 25% to 52% even as the effluent BOD concentration followed the trend of influent BOD concentration.

Solano et al, (2004) presented results of treatment efficiency of a pilot-scale subsurface flow constructed wetland planted with Phragmites australis remove BOD, COD, and TSS. The TN removal efficiency decreased at 4 days HRT but increased at 6 days. There was only slight increase (2%) in removal efficiency when HRT increased from 6 days to 8 days. There was an increasing trend in TP removal efficiency as the HRT increased from 2 days to 8 days but there was a slight decrease (2%) at 4 days HRT which may probably be attributed to decrease in influent TP concentration (Figure 8).

Phragmites australis were able to establish successfully in wastewater treatment as reported by Calheiros et al, (2008). The treatment performance as reported by Calheiros et al, (2008) was higher than the present study as the former use two-stage HSFCW in series planted with Phragmitesaustralis.

4.4 Horizontal Flow Constructed Wetland (HFCW) Field Trial Results

Figure 7a and 7b shows the reduction in concentration of various parameters with respect to time. As the detention time increases, the reduction percentage is also increased, a detention period of 5 days is given for the constructed wetland. The removal efficiencies of various parameters after 5th day were 63.16 % for BOD, 62.96 % for COD, 52.63 % for TDS, 64.29 % for Nitrate, 46.60 % for Phosphate, 44.27 % for Potassium.

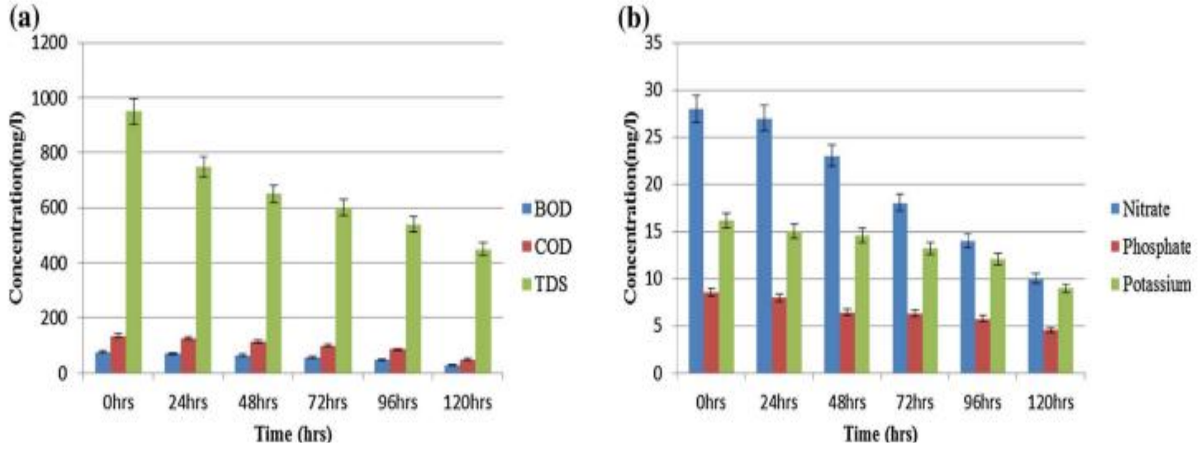

Figure 7. Reduction in Concentration from Influent and Effluent of Wastewater. (a) BOD (Biological Oxygen Demand), COD (Chemical Oxygen Demand) and TDS (Total Dissolved Solids), (b) Nitrate, Phosphate, and Potassium (Adapted fromKarpagam, M., and S. Sivasubramanian, 2015).

The interactions between abiotic and biotic components as well as external factors could influence the treatment efficiency of CW systems. Several parameters including CW physical configurations, hydraulics, substrates, plant species diversity, dissolved oxygen (DO) level, climatic conditions (e.g., temperature/season) etc. impact the pollutant removal performance of CW systems (Zhu et al., 2014; Herrera-Cárdenas et al., 2016). The pollutant removal efficiency varies with a change of CW system configurations as reported by Chen et al. (2016). Chen et al. (2016) compared the antibiotics removal performance of three different CW configurations namely SF and SSF (VF and HSF CW) wetland facilities, and SSF systems (89.1–98.9%) show higher performance for the removal of antibiotics (e.g., erythromycin) than the SF system (76%). Moreover, among the HSF and VF configurations, HSF (98.9%) had higher capability for the removal of pollutants compared to the VF unit (89.1%). Xu et al. (2016) also observed differences in the reduction of pollutants in pilot-scale HSF-based and VF-based CW systems. The former type showed high performance for the removal of COD (74%) and ammonia (79%), while the latter one was effective mainly for the total nitrogen removal (64%) (Xu et al., 2016).

Hydraulic loading rate (HLR) could affect the performance of CW systems, and in most of the cases, the pollutant removal efficiency decreased with an increase of HLR (Trang et al., 2010). In HSF-based CW systems treating a mixture of wastewater and stormwater, it was observed that the removal efficiency of TN and TP constantly decreased with a gradual increase of HLR (31, 62, 104 and 146 mm/day). Also, the TN and the TP removal efficiency decreased from 84 to 16% and from 99 to 72%, respectively with the rise of HLR from 31 to 146 mm/day (Trang et al., 2010). In a pilot-scale HSF CW system, the removal efficiency of COD, TN and TP was 95, 95 and 95%, respectively at a HLR of 0.025 m/day, but the removal efficiency decreased to 91, 87 and 89% when the HLR was doubled (0.05 m/day) (Angassa et al., 2019).

Hydraulic retention time (HRT) is one of the important operational parameters which impacts the effectiveness of CW systems. Sultana et al. (2016) investigated the COD removal from cheese whey wastewater in pilot-scale unplanted and planted (reed: Phragmitesaustralis) HSF-based CW systems at four different HRTs (1, 2, 4 and 8 days). In both CW systems, the percentage of COD removal was reduced with a decrease of HRT, i.e., in an unplanted CW system; the percentage of COD removal decreased from 100 to 76% when HRT was reduced from 8 days to 1 day. However, in the vegetated cell, a similar decrease of performance was also noticed (a reduction from 100 to 76% with a reduction of HRT from 8 days to 1 day). In VF-based CW systems, Sarmento et al. (2013) evaluated the influence of four distinct HRTs (1, 2, 3 and 4 days) on the decontamination of various pollutants from swine wastewater. It was observed that the pollutant removal efficiency was enhanced with the rise of HRT up to 3 days, and then decreased. In a recent pilot-scale study on the treatment of synthetic wastewater using a vertical subsurface flow CW vegetated with two plants namely Typhalatifolia and Phragmitesaustralis, the pollutant (e.g., COD) removal efficiency constantly increased with the rise of HRT from 2 days (69.4%), 4 days (77.6%), 6 days (86.3%), 8 days (86.4%) and 10 days (88.8%) (Shruthi and Shivashankara, 2021b).

Plants are one of the important components in CW systems and could influence the decontamination performance of wetlands. Sarmento et al. (2013) compared the performance of three plant species namely Cyperus sp. (grass), Heliconiarostrata (shrub) and Hedychiumcoronarium (herbaceous) for the removal of various pollutants from swine wastewater in VF-based CW systems. In addition to plant species diversity, plant root characteristics (length, biomass, architecture, etc.) could also impact the rate of uptake of pollutants since among the three types of plants namely Canna (flowering plant), Phragmitesaustralis (reed) and Cyprus papyrus (flowering seed plant) vegetated in VF-based CW systems investigated for the decontamination of municipal wastewater, the uptake of nitrogen and phosphorus as well as the removal faecal indicator bacteria was higher in Canna than the other two vegetations (Abou-Elela and Hellal, 2012). Canna showed better performance since the roots were spread broadly and uniformly in the CW filter bed. Diversity of vegetation species in CW influenced the removal of nitrogen more compared to that of phosphorus (Liang et al., 2017).

Microbial degradation is one of the important pathways for removal of pollutants from wastewater/stormwater in CW systems. Thus, in addition to CW operational parameters and surrounding climatic conditions, the abundance and diversity of various functional microbial communities (nitrifiers, denitrifiers, organic carbon degraders, etc.) could influence the treatment performance of CW systems(Zhang et al., 2018 andZhou et al., 2020).

4.5 Recommendations for Enhanced Efficiency of Horizontal Flow Constructed Wetland

(i) Horizontal subsurface flow (HSSF) systems require coarse media (10–25 mm) to enhance flow and minimize clogging. Hybrid systems benefit from a mix of finer (4–10 mm) and coarse substrates (10–40 mm) for improved nitrification.

(ii) A longer hydraulic retention time (HRT) improves nutrient removal; hybrids are effective at four days, whereas HSSF requires at least three days.

(iii) Loading frequency and distribution: Intermittent loading (four to six times daily) increases oxygenation in hybrids, and even an influent distribution helps prevent clogging in horizontal systems.

(iv) Vegetation Management: Regular harvesting of plants like *P. Australis* enhances pollutant uptake and decreases organic build-up.

(v) Operational Considerations: Effective influent control is vital for preventing clogging; future designs should prioritize balanced flow inlets.

4.6 Review of Research Studies on Biocharand Evaluation of Outcomes

4.6.1 RemovalofOrganics

Studies have shown that, CFWs with different configurations operated under identical conditions showed significant differences in their performances (p<0.05) in removing COD. With a COD concentration of 100mg/L in the influent, the COD levels in the effluent of each CFW were below 25 mg/L for reactors R1(P + A) and R3(P + BA), with removal rates exceeding 75%, indicating substantial organic COD removal by CFWs containing biocharand plants. As shownin Figure 9(a)–(b), the COD concentrations in the effluent from the biochar and bioactive biochar were consistently low across all reactors for different cycles, demonstrating the effectiveness of modified corncob biochar in removing organic COD. The clear effect of plants along with biochar was noted (p<0.05) inreducing COD in R1(P+A) and R3(P+BA) compared to R2(A) and R4(BA), indicating the synergistic roles of plants, microbes, and biochar in removing organics. Furthermore, significant COD removal was observed in R2(A) and R4 (BA) compared to R5(P), likely due to the roles of biochar through sorption and biodegradation via microorganisms (Bano et al., 2023; Qietal.,2024). There actor setup, R3(BA), exhibited the best performance, with the lowest COD concentration ineffluents (16.27–18.67mg/L)<20mg/L for all three runs, as shown in Figure 9. This better removal effect was attributed to the bioactive biochar, which aided the microbial community. Similar findings were reported by Qi et al. (2024) in modified biochar and Zhang et al. (Zhang et al., 2023) in microbe-assisted CWs. Similar trends were observed for TOC reduction in all systems.

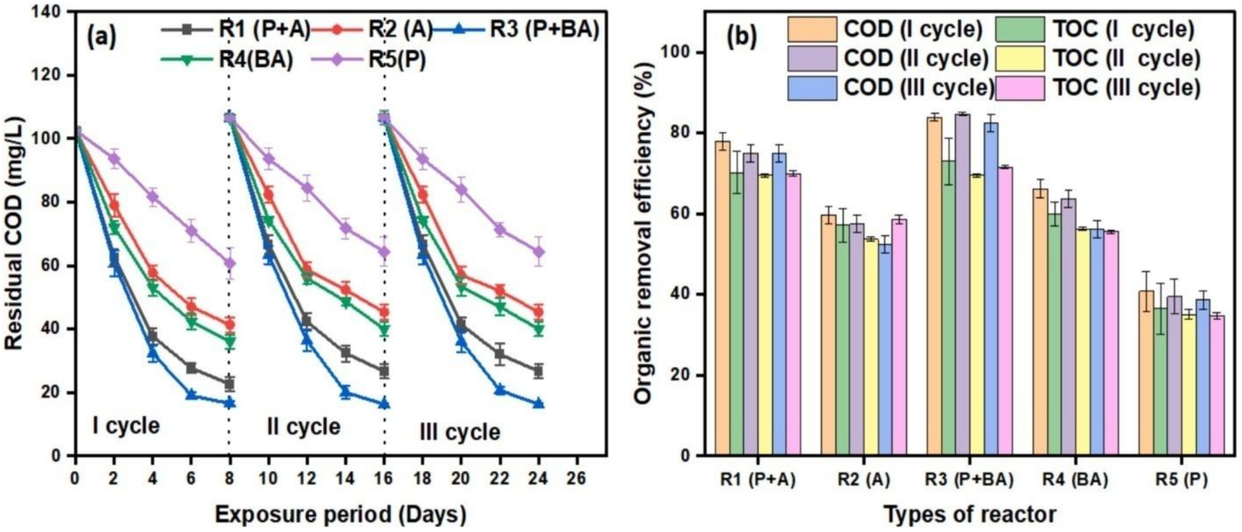

Figure 9: (a) Residual COD and (b) COD removal efficiency in reactors R1 to R5 during cycles I, II, and III.(Adapted from Karki, B. K., & Philip, L., 2026).

At the end of the experiment, the microbial biomass (total protein content) attached to the biochar in different setups was determined to be 6.50±0.50mg/g, 5.34±0.76mg/g, 11.50±0.51mg/g, and 10.30±0.91mg/g for Reactor R1(P+A), R2(A), R3(P+BA), and R4(BA), respectively. The significantly higher biomass protein content (about twice, *P* value <0.05) in reactors R3 (P + BA) and R4 (BA) compared to R1(P+A) and R2(A) is likely due to the use of pre-acclimatized biomass prior to the experiments.

As a result, CFW setups incorporating bioactive or biochar-supported systems with plants showed higher overall organic removal than other reactors. This suggests that adding biochar/bioactive biochar significantly enhances treatment performance, likely due to improved sorption and favorable conditions for biodegradation (Zhuanget al.,2022b).

However, overallpollutant removal was influenced by two key factors: first, the low net coverage by plants and biochar columns (<20%) meant the remaining area functioned as an open pond, which also contributed to pollutant removal through natural processes (Pavlineri et al., 2017). Second, the absence of mechanical agitation, designed to mimic natural systems, slowed the contact between pollutants and treatment media, while in plant-only systems (such as A or BA), about 50% of openings remained exposed, allowing photo degradation to aid removal (Shenetal.,2022b). Despite these limitations, incorporating biochar improved treatment efficiencyby30–40%, exceeding the<10% improvement reported by Chandetal. (2022) for biochar-amended constructed wet lands. Similarly, Shen et al. (2022b) observed comparable phosphorus removal efficiencies in both plant-based systems and CFWs enhanced with AAC blocks. These results align with findings from Bano et al. (2023), demonstrating that biochar and bacterial intensification in floating treatment wetlands can substantially improve pollutant reductions, offering a low-cost, eco-friendly solution for treating polluted waters.

4.6.2 Removal of Nutrients

In CFWs, suspended roots remove nutrients through biosynthesis andrhizo-filtration (Pavlineri et al., 2017). In this study, the removal of nutrients such as different nitrogen species (TN, NO_3-N, NH_4-N), and PO^{-3}-P_4 were also examined across different configurations of CFWs (Figure 10). Nitrate removal ranged from 80% to 92% invarious setups, with over 90% reduction observed in the R3 (P +BA) reactor. Similar removal trends were observed for TN and NH_4-N in the R3(P +BA) reactor.Various studies have mentioned a significant reduction of nitrogen from CFWs. The high reductions of TN removal (above 98%) were reported for *Iris pseudacorus* plants supported FTW by Keizer-Vleket al. (2014). *Pontederia cordata* and *Juncus effuses* assisted CFWs were reported to remove 84.3%-88.9% and 35.5%-66.3% of TN from polluted water, respectively (Spang leretal., 2019 a, 2019 b). Moreover, the TN reduction improved by 1.39 to 1.40 times in the R1(P+A) and the R3(P +BA) compared to the R5(P) reactor. These improvements indicate that amended corn cob modified biochar can promote nitrification and denitrification activities (Qietal.,2024). Similar increments in TN reduction up to1.78 times were reported by Banoetal. (2023) due to the amended biochar in CFWs.

The significant TN reduction (*P* value<0.05) in R1(P+A) and R3(P+BA) compared to R5(P) is attributed to the synergistic effects of mi-cro organisms, plant up take, and sorption capacity of biochar (El Barkaouiet al., 2023). Other studies have also reported a noteworthy reduction of nitrogen in the CFW system (Bano et al., 2023; Shahid et al.,2019). It has been further reported that ammonium removal in CFW ranges from 24% to 100%, depending on plant species, influent load, input system (batch/ continuous), and other environmental factors (Sharmaetal.,2021). Similarly, in CFWs, phosphate removal primarily occurs through plant uptake, microbial activity, sorption, and precipi-tation (Sharmaetal.,2021). Plants in CFWs absorb phosphorus from the water column through their roots, while microorganisms immobilize phosphorus through microbialassimilation. Similar to TN, reactors R1(P+A) and R3(P+BA) showed asignificant reduction (*P*value<0.05) of phosphorus compared to other reactors, demonstrating the removal enhancement due to addition of biochar.

TN and TP accumulation in biochar and plants were also evaluated at the end of experiments after 24 days, as shown in (Figure 10(c) and (d)). TN accumulation inbiochar wasobserved torange from5.99 to 6.46 mg/g dry weight (DW) of biochar in the biochar-amended system. In contrast, a reduction in accumulation was noted in the bioactive biochar-amended CFW system, where TN levels ranged from 3.61 to 4.09 mg/ g DW of biochar. Similarly, in plants, TN accumulation was between 0.87 and 0.90mg/g of DW of plants compared to those in plants on the initial day. Similar results were observed for TP accumulation with 1.81–2.30mg/g of D Win biochar and 0.11 to 0.17mg/g of D Win plants. Moreover, mass balance analysis (Figure 10(e) and (f)) revealed that direct plant uptake of TN was limited to 2%, while TN accumulated in biochar ranged from 8.23 to 14.71%. In case of TP, slightly more accumulation of phosphorous was observed upto 27.88–35.46% in biochar. The substantial reduction of TN (52 to 63%) and TP (10 to 36%)was attributed to other processes, including microbial processes and other activities within the CFWsystems. Narayanasamydamodaran et al.(2024) reported TN and TP accumulation of 48.10mg/g of DW and 2.82 mg/g of DW of Vetiver plants in bioretention cells, respectively. The lower TN and TP accumulation observed in bioactive biochar column compared to biochar column may be due to enhanced microbial activity on the bioactive biochar surfaces. Microbescolonizing biocharcan actively transform nitrogen and phosphorous compounds through bio-logical processes, inhibiting static accumulation (Chand et al., 2022; Shen et al., 2022a).

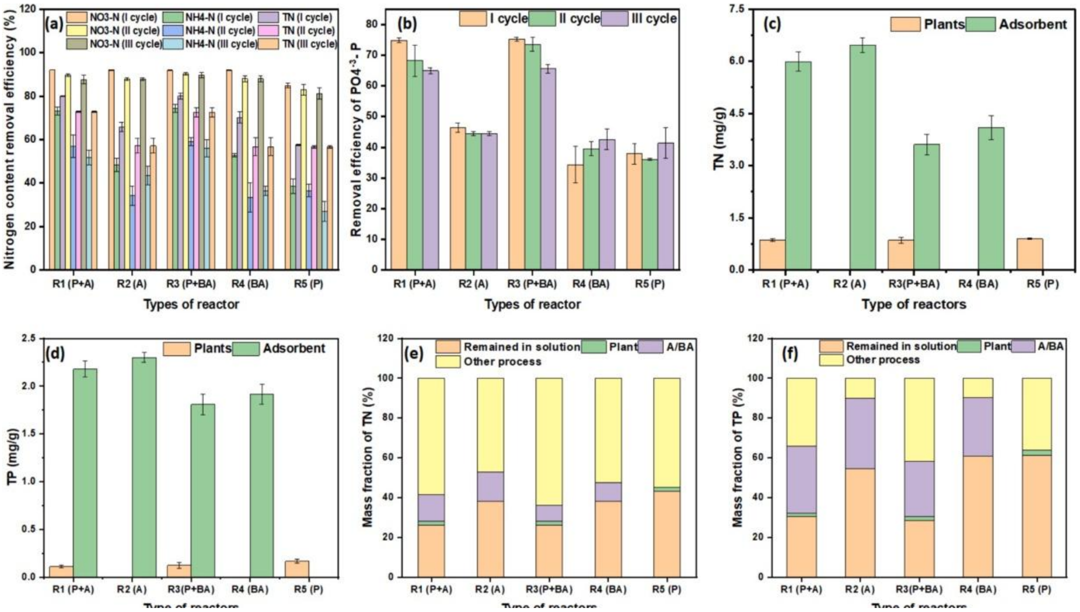

Figure 10: Removal of (a) nitrogen species (TN, NH4-N, NO3-N), (b) phosphorous, during I cycle, II cycle, and III cycle runs in different CFWs configurations (R1 to R5), (c) accumulation of TN in plants and biochar, (d) accumulation of total phosphorous content in plants and biochar, (e) fate of TN and (f) Fate of TP.(Adapted fromKarki, B. K., & Philip, L., 2026).

4.7 Crop Quality (Lettuce and Kale)

To assess the quality of lettuce and kale, physicochemical and microbiological characteristics will be compared with selected standards and macronutrients and micronutrients against optimum ranges and phytotoxic thresholds found in related literature (Hartz et al., 2007; Marschner, 2012). Water content in lettuce and kale among the six treatments should fall in the 93.0%–94.9% range; thus, not presenting significant differences. To prevent inaccuracies, irrigation with different waters will be evenly maintained throughout the experiment for the drip irrigation system, according to their technical specifications. However, all treatments should comply with the commercial minimum weight of 100 g for lettuce and kale (classes I and II) grown under protection (OECD, 2002; UNECE, 2012). Total N concentrations presented significant differences in regard to the irrigation waters, and all of them are slightly over the optimum range (33–48 g/kg) for this type of crop (Hartz et al., 2007).

The pollution parameters evaluated were faecal coliforms and helminth eggs. Water quality was monitored for two months, and their concentration levels ranged from 3 to 4 log units of faecal coliforms per 100 mL and from 6 to 15 eggs of helminth per L. Regarding the evaluated product of consumption (lettuce), the concentration of faecal coliforms ranged from 7 × 102 to 1.8 × 103 per 10 g, and the concentration of helminth eggs ranged from 6 to 9 per 100 g. The annual risk of infection was 10−2 for Ascaris and 10−1 for E. coli. This study is relevant for the development of risk assessments for possible infections caused by helminths and E. coli (see Figure 8).

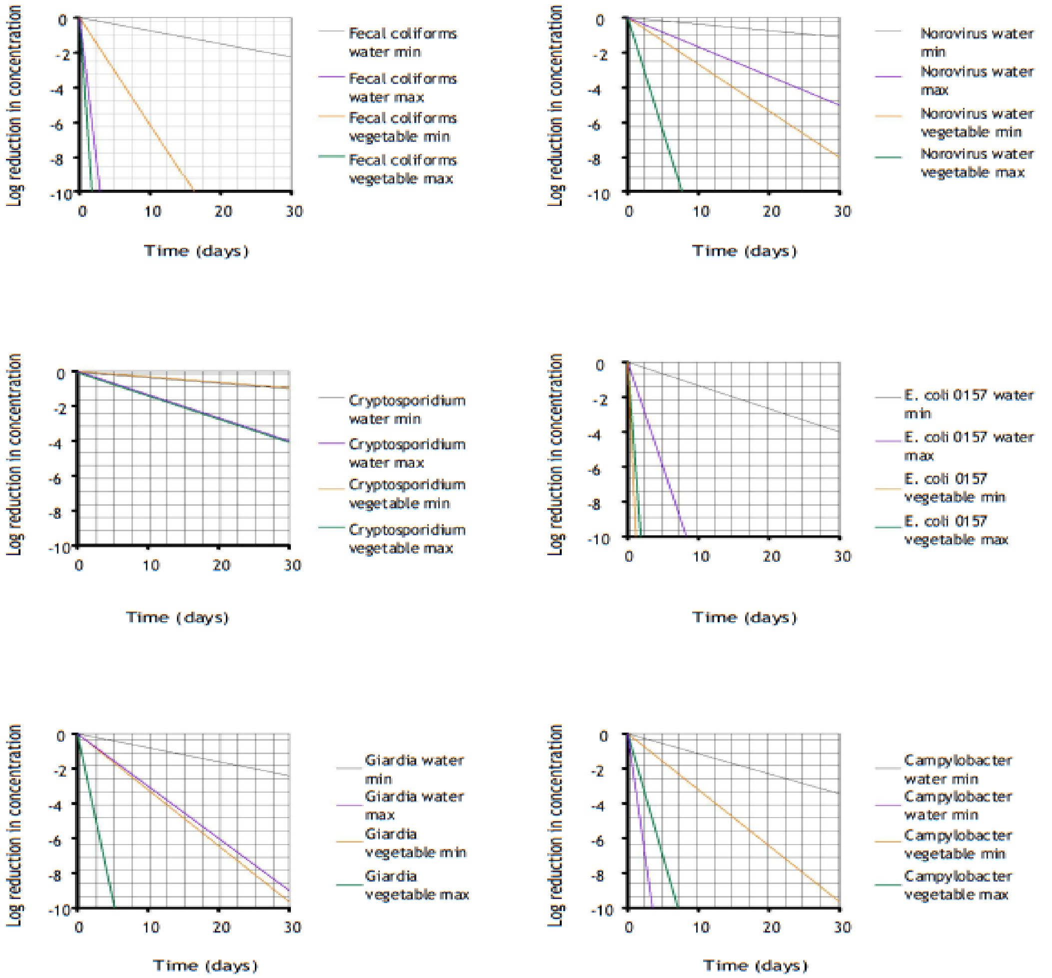

Figure 8. Modelled Survival Rates in Water and on Vegetables

(Adapted from Pond, K. et al. (2007), B17005 Review of the Use of Water in UK Agriculture)

5. DISCUSSIONS

5.1 Environmental Benefits

The use of treated wastewater promotes environmental sustainability by connecting rural and urban areas, reducing pollutant discharge, and minimizing groundwater contamination while effectively utilizing nutrients from wastewater. A management plan for the Caroni River Basin

(CRB) aims to protect ecological integrity and conserve biodiversity through sustainable resource use, emphasizing a participatory approach rather than top-down legislation. Implementing vertical-flow constructed wetlands will help manage stormwater runoff, and educating farmers on system management will address health and environmental risks.

Reusing agricultural wastewater can save costs associated with groundwater extraction, as pumping groundwater can account for up to 65% of irrigation expenses. Additionally, the nutrients in wastewater can lower fertilizer costs, creating a closed nutrient cycle and preventing excess nitrogen and phosphorus from re-entering water bodies. This practice has been shown to improve crop yields and reduce the need for fertilizers, ultimately decreasing water body eutrophication and farmers' agrochemical expenses.

5.2 Social/Community Benefits

Regulatory and institutional improvements, alongside awareness campaigns, will empower the population regarding drought management and enhance their involvement in related decision-making processes. Infrastructure enhancements, such as treated wastewater supply and solar-powered drip irrigation systems, will improve the quality of life for farmers by ensuring a reliable water source and promoting health by reducing pesticide use and pollution. These measures are expected to conserve water, improve public health, and reduce the spread of waterborne diseases, ultimately benefiting farmers through better marketability of their produce and providing consumers with healthier food options. Based on regulatory aspects, agricultural wastewater reuse can contribute to the justification of suitable investment policies and financing mechanisms for pollution control and prevention.

5.3 Economic Benefits

Treated wastewater can create a financial advantage and increase revenue for farmers by avoiding development costs, increasing land and property values, boosting tourism activities in dry regions, generating additional revenue from recycled water sales, creating secondary revenue for customers and industries, reducing or eliminating the need for commercial fertilizers, and lowering water treatment costs for downstream users.

An implicit economic benefit of agricultural wastewater reuse is the valuation of treated water discharged for human consumption, as this use is considered to be of the highest priority. In some countries, wastewater reuse contributes to reducing the municipal cost of sourcing water, which can be achieved through more expensive means.

5.4 Legal Benefits

The findings of this study will provide valuable insights to support the safe and sustainable reuse of treated wastewater in agriculture, promoting resource conservation and enhancing agricultural practices. This pilot study seeks to catalyze the development of programmes for the national-scale adoption of wastewater reuse schemes and improved policies and procedures, such as

1. Policy and Administrative Measures
2. Policy Development Driving Forces
3. Legislation: Water Pollution Regulation, Miscellaneous Water-Related Laws,

Occupational Safety and Health Act, Role and Function of the Pesticides and Toxic Chemicals Control Board, Obligations under International Instruments

1. Development of Safe and Effective Wastewater Reuse and Irrigation Water Management
2. Development of a GIS-Based Water and Wastewater Management Assessment Model

Treated wastewater initiatives will lead to improvements through increased policy awareness, alignment with international treatment regulations, and the development of guidelines for wastewater reuse.

5.5 Case Studies in the Caribbean

Scope of Projects:

- Construction and rehabilitation of wastewater treatment plants.
- Installation of new sewage collection systems to reduce untreated wastewater discharge.
- Capacity building and training for local communities and stakeholders on sustainable wastewater management practices.
- Public awareness campaigns to educate the public on the importance of proper wastewater management.

The Projects achieved several positive Outcomes:

- Improved wastewater treatment capacity and efficiency, leading to better water quality in affected areas.
- Reduction in pollution and environmental impact from untreated wastewater.
- Increased community engagement and awareness about wastewater management issues.
- Enhanced resilience to climate change impacts through improved water resource management.

Lessons Learnt from Case Studies

- Community Involvement is crucial for the success of IWWM projects.
- Sustainable Practices and Infrastructure Upgrades are essential for long-term success.
- Capacity building and Public Awareness campaigns are vital for changing behaviours and ensuring project sustainability.

This case studies of the Caribbean countries listed, highlight the importance of integrated approaches to wastewater management and the positive impact such projects can have on both the environment and local communities.

5.5.1 Jamaica: Wastewater Reuse in Crop Production

Jamaica has implemented several initiatives that utilize treated wastewater for irrigation in crop production, particularly in the cultivation of vegetables such as tomatoes and lettuce. The National Irrigation Commission developed a pilot project that utilized aerobic treatment systems to enhance water quality before municipal irrigation. This case study illustrated that reclaimed water significantly contributed to water supply sustainability, especially during dry seasons.

5.5.2 Dominican Republic: Constructed Wetlands for Rice Cultivation

In the Dominican Republic, a project implemented constructed wetlands to treat municipal wastewater before it was used for irrigation in rice fields. The system effectively removed contaminants, demonstrated successful pollutant reduction, and improved water quality for agricultural use. The study highlighted how the wetlands provided additional benefits, such as supporting local biodiversity.

5.5.3 Trinidad and Tobago: Pilot Study on Horizontal Flow Constructed Wetlands

A pilot project at the Guanapo Landfill in Trinidad and Tobago focused on using a Horizontal Flow Constructed Wetland System (HFCWS) to treat leachate, with preliminary findings showing improved water quality that exceeded WHO standards. The treated water was then tested for suitability in agricultural applications, demonstrating the potential of HFCWS as a cost-effective and viable technology for safe water reclamation in rural areas.

5.5.4 Cuba: Integrated Ecological Agriculture and Wastewater Treatment

In Cuba, ecological agriculture practices have been integrated with wastewater treatment systems, utilizing biogas digesters and biofilters to treat waste effectively. The treated effluent is used for irrigation in urban and peri-urban farming. This approach not only improves crop yield but also enhances food security while addressing both sanitation and water scarcity issues.

5.5.5 Bahamas: Water Reclamation for Sustainable Farming

A project in the Bahamas focused on water reclamation technologies involving anaerobic digestion and constructed wetlands to treat wastewater from agricultural runoff as well as municipal sources. The reclaimed water was reused for irrigation in agricultural fields. The outcomes of this initiative showcased improved crop productivity and soil health, contributing to sustainable agricultural practices.

5.5.6 Barbados: Wastewater Irrigation in Vegetable Production

In Barbados, a project aimed at reusing treated wastewater for irrigation in the production of vegetables demonstrated significant increases in yield and quality compared to traditional irrigation methods. The project involved educating farmers on the safe use of treated wastewater, which ultimately led to enhanced community acceptance and willingness to adopt such practices.

5.5.7 Saint Lucia: Aquaponics and Wastewater Recycling

An innovative approach in Saint Lucia involved integrating aquaponics systems that utilized wastewater from fish farming. The nutrient-rich water was circulated to vegetable crops, effectively treating the wastewater while creating a sustainable food production system. This project emphasized the dual benefit of enhancing agricultural outputs and promoting efficient water use.

5.5.8 Belize

Case Study titled Los Porticos Villas Wastewater Treatment Project

Los Porticos Villas in Placencia, Belize faced significant wastewater management challenges, including untreated wastewater discharge and environmental pollution. The project aimed to address these issues by implementing a sustainable and cost-effective wastewater treatment solution.

Objectives:

The project had several key objectives:

1. Reduce untreated wastewater discharge to protect the environment.
2. Improve water quality in the area.
3. Implement a cost-effective and sustainable wastewater treatment system.

Implementation:

Designing a unique wastewater treatment system that combined a septic/balancing tank, biological active filters, humus sludge handling, a polishing filter (artificial wetland), and disinfection.

Constructing a gravity sewer system to feed the treatment plant, minimising visual impact and odours.

Awarding the contract to a local contractor to ensure community involvement and support.

5.5.9 Cuba, Dominica, Guadeloupe, Martinique, and Saint Lucia

The CARIBSAN project is an inter-Caribbean cooperation initiative aimed at promoting the use of constructed wetlands for wastewater treatment in the Caribbean region. The project is co-financed by the European Union through the INTERREG Caribbean program and involves partners from several Caribbean countries, including Cuba, Dominica, Guadeloupe, Martinique, and Saint Lucia.

Objectives

- Promote nature-based solutions for wastewater treatment using constructed wetlands.
- Improve wastewater treatment in fragile coastal ecosystems and sensitive areas, such as swimming areas.
- Enhance resilience to natural hazards, such as cyclones, by using locally adapted plants and substrates.

Implementation

- Constructed wetlands using local plants like Heliconia (birds-of-paradise) combined with substrates to filter and treat wastewater.
- Training and capacity building for sanitation professionals in the Caribbean on the use of constructed wetlands.
- Preliminary studies and pilot projects to demonstrate the effectiveness of constructed wetlands in different Caribbean countries.

Outcomes

- Successful implementation of constructed wetlands in Martinique and Guadeloupe, demonstrating their effectiveness and cost-efficiency.
- Increased awareness and adoption of nature-based solutions for wastewater treatment in the Caribbean.
- Enhanced collaboration among Caribbean countries and international partners in promoting sustainable wastewater management.

The CARIBSAN project highlights the potential of nature-based solutions to address wastewater treatment challenges in the Caribbean, offering a sustainable and resilient approach to protecting the environment and public health.

6. CONCLUSION

The WWR prototype reclamation system investigated in this study is expected to effectively examine the primary environmental, agricultural, and public health issues associated with reclaimed water, particularly salinity and pathogenicity. Empirical studies of the WWR prototype will evaluate the capture of contaminants within the structure's layers and the long-term efficacy of the geotextile membrane in accumulating pollutants. Analysis of water quality suggests that the infiltration technologies employed in the gravel structure successfully remove typical pollutants found in treated wastewater effluents. Findings related to crop water quality, agronomic factors, and microbiological aspects indicate that the WWR prototype, combined with vertical flow constructed wetlands and solar-powered automated drip irrigation systems, represents advanced technologies suitable for safe water reclamation in agricultural production. Although the WWR prototype shows promise in producing high-quality reclaimed water for vegetable crop cultivation, it is crucial to strive for optimal, fit-for-purpose treatment performance. Defining acceptable ranges for irrigation water quality based on crop type, agronomic standards, and microbiological guidelines will enable the refinement of the prototype reclamation system to meet specific requirements. This strategy will ensure the efficient utilization of valuable plant nutrients while maintaining environmental compliance and mitigating risks in agricultural production. Tolerance ranges in the quality of irrigation waters regarding the type of crop, as well as in the agronomic and microbiological standards and guidelines, will fine-tune the prototype reclamation system according to specific needs, thereby retaining the most valuable plant nutrients while ensuring environmental compliance and a less risky agricultural production. This research will seek to catalyse the development of programs for the national-scale adoption of wastewater reclamation schemes for agricultural irrigation and enhance related policies and procedures.

Acknowledgements

The authors would like to acknowledge the support of The University of the West Indies, St. Augustine, Trinidad and Tobago and the Faculty of Engineering, Department of Civil and Environmental Engineering for providing the Laboratory Facilities and Equipment for this research. Special thanks to the Caribbean Industrial Research Institute (CARIRI) for conducting tests and analyses of the bio-filter and substrate materials.

REFERENCES

1. **Abou-Elela, S. I., Golinelli, G., El-Tabl, A. S., &Hellal, M. S. (2014).** Treatment of municipal wastewater using horizontal flow constructed wetlands in Egypt. Water Science and Technology, 69(1), 38–47. https://doi.org/10.2166/wst.2013.530
2. **Akram, M.T., Rahman, S., Al-Busaidi, W. and Khan, I. (2022)** Towards sustainable application of wastewater in agriculture: a review on reusability and risk assessment. *Agronomy*, 12(7), 1672. https://doi.org/10.3390/agronomy12071672
3. **Bano, S., Tahira, S.A., Naqvi, S.N.H., Tahseen, R., Shabir, G., Iqbal, S., Afzal, M., Amin, M., Boopathy, R. and Mehmood, M.A. (2023)** Improved remediation of amoxicillin-contaminated water by floating treatment wetlands intensified with biochar,

nutrients, aeration, and antibiotic-degrading bacteria. *Bioengineered*, 14(1), pp. 1–14.https://doi.org/10.1080/21655979.2023.2252207

4. Bellahsen, N., Kertész, S., Pásztory, Z., &Hodúr, C. (2018). Adsorption of nutrients using low-cost adsorbents from agricultural waste and by-products – Review. Progress in Agricultural Engineering Sciences, 14(1), 1–30. https://doi.org/10.1556/446.14.2018.1.1
5. **Calheiros, C.S.C., Rangel, A.O.S.S. and Castro, P.M.L. (2008)** Evaluation of different substrates to support the growth of *Typha latifolia* in constructed wetlands treating tannery wastewater over long-term operation. *Bioresource Technology*, 99(15), pp. 6866–6877. https://doi.org/10.1016/j.biortech.2007.12.043
6. **Calheiros, S.C., Rangel, A.O.S.S. and Castro, P.M.L. (2007)** Constructed wetland systems vegetated with different plants for the treatment of tannery wastewater. *Water Research*, 41(8), pp. 1790–1798. https://doi.org/10.1016/j.watres.2007.01.012
7. **Çeçen, F. and Aktaş, Ö. (2011)** Evaluation of biological activated carbon (BAC) process in wastewater treatment secondary effluent for reclamation purposes. *Desalination*, 265(1–3), pp. 266–273. https://doi.org/10.1016/j.desal.2010.07.060
8. **Chand, N., Suthar, S., Kumar, K. and Singh, V. (2022)** Removal of pharmaceuticals by vertical-flow constructed wetlands with different configurations: effect of inlet load and biochar addition in the substrate. *Chemosphere*, 307, 135975. https://doi.org/10.1016/j.chemosphere.2022.135975
9. **Chand, N., Suthar, S., Kumar, K. and Tyagi, V.K. (2021)** Enhanced removal of nutrients and coliforms from domestic wastewater in cattle-dung biochar-packed *Colocasia esculenta*-based vertical subsurface-flow constructed wetland. *Journal of Water Process Engineering*, 41, 101994. https://doi.org/10.1016/j.jwpe.2021.101994
10. **Drechsel, P., Qadir, M. and Wichelns, D. (eds.) (2015)***Wastewater: economic asset in an urbanizing world*. Dordrecht: Springer. https://doi.org/10.1007/978-94-017-9545-6
11. **El Barkaoui, S., Mandi, L., Aziz, F., Del Bubba, M. and Ouazzani, N. (2023)** A critical review on using biochar as a constructed wetland substrate: characteristics, feedstock, design and pollutant removal mechanisms. *Ecological Engineering*, 190, 106927. https://doi.org/10.1016/j.ecoleng.2023.106927
12. **Jaramillo, M.F. and Restrepo, I. (2017)** Wastewater reuse in agriculture: a review of limitations and benefits. *Sustainability*, 9(10), 1734. https://doi.org/10.3390/su9101734
13. **Jiménez, B. and Asano, T. (eds.) (2008)***Water reuse: an international survey of current practice, issues and needs*. London: IWA Publishing.
14. **Karki, B. K., & Philip, L. (2026).** Evaluating the efficacy of biochar columns for two pharmaceuticals, methyl paraben and nutrient removal in constructed floating wetlands. Science of the Total Environment, 1020, 181573. https://doi.org/10.1016/j.scitotenv.2026.181573
15. **Karpagam, M., and S. Sivasubramanian (2015).** "Domestic wastewater treatment performance using constructed wetland." Sustainable Water Resources Management, Vol. 1, 2015, pp. 89–96. Springer.

16. **Keizer-Vlek, H.E., Verdonschot, P.F.M., Verdonschot, R.C.M. and Dekkers, D. (2014)** The contribution of plant uptake to nutrient removal by floating treatment wetlands. *Ecological Engineering*, 73, pp. 684–690. https://doi.org/10.1016/j.ecoleng.2014.09.081
17. **Lazarova, V., Asano, T., Bahri, A. and Anderson, J. (eds.) (2013)***Milestones in water reuse: the best success stories*. London: IWA Publishing. https://doi.org/10.2166/9781780400716
18. **Li, J. and Wen, J. (2016)** Effects of water management on transport of *Escherichia coli* in the soil-plant system for drip irrigation using secondary sewage effluent. *Agricultural Water Management*, 178, pp. 12–20. https://doi.org/10.1016/j.agwat.2016.08.036
19. **Lyu, S., Chen, W., Zhang, W., Fan, Y. and Jiao, W. (2016)** Wastewater reclamation and reuse in China: opportunities and challenges. *Journal of Environmental Sciences*, 39, pp. 86–96. https://doi.org/10.1016/j.jes.2015.11.012
20. **Ministry of Agriculture, Land and Marine Resources (MALMR) (2007)***Projected agricultural water requirement to the year 2025*. Port of Spain, Trinidad and Tobago: Government of Trinidad and Tobago.
21. **Narayanasamydamodaran, S., Kumar, N. and Zuo, J. (2024)** The role of plant uptake in total phosphorus and total nitrogen removal in vegetated bioretention cells using vetiver and cattail. *Chemosphere*, 364, 143276. https://doi.org/10.1016/j.chemosphere.2024.143276
22. **Pavlineri, N., Skoulikidis, N.T. and Tsihrintzis, V.A. (2017)** Constructed floating wetlands: research, design, operation and management aspects and data meta-analysis. *Chemical Engineering Journal*, 308, pp. 1120–1132. https://doi.org/10.1016/j.cej.2016.09.140
23. **Pereira, L.S. (2017)** Water, agriculture and food: challenges and issues. *Water Resources Management*, 31, pp. 2985–2999. https://doi.org/10.1007/s11269-017-1664-3
24. **Peters-Everson, J. and Joseph, V. (2015)** Evaluation of compliance with the Water Pollution Control Rules in Port of Spain, Trinidad. *West Indian Journal of Engineering*, 38(1), pp. 21–32.
25. **Pond, K., Charles, K., &Pedley, S. (2007)**. Review of the use of Irrigation Water in UK agriculture and the potential risks to food safety (Report B17005). London: Food Standards Agency.
26. **Qi, Y., Zhong, Y., Luo, L., He, J., Feng, B., Wei, Q., Zhang, K. and Ren, H. (2024)** Subsurface constructed wetlands amended with modified biochar for advanced tailwater treatment: performance and microbial communities. *Science of the Total Environment*, 906, 167533. https://doi.org/10.1016/j.scitotenv.2023.167533
27. **Rawlins, B.G., Ferguson, A.J., Chilton, P.J., Arthurton, R.S., Searle, D.E. and Milodowski, A.E. (1998)** Review of agricultural pollution in the Caribbean with particular emphasis on small island developing states (SIDS). *Marine Pollution Bulletin*, 36(9), pp. 658–668. https://doi.org/10.1016/S0025-326X(98)00053-2
28. **Roopnarine, R., Baird, K., Hosein, M., Jackson, R., Salim, S., Cephas, A., Gangapersad, S., Govia, S.-J. and Cashman, A. (2023)** Integrating wastewater reuse into water

management schemes of Caribbean SIDS: a Trinidad and Tobago case study. *Water Policy*, 25(12), p. 174. https://doi.org/10.2166/wp.2023.174

29. **Scholz, M. (2013)** Water quality improvement performance of geotextiles within permeable pavement systems: a critical review. *Water*, 5(2), pp. 462–479. https://doi.org/10.3390/w5020462
30. **Shahid, M.J., Arslan, M., Siddique, M., Ali, S., Tahseen, R. and Afzal, M. (2019)** Potential of floating wetlands for treatment of polluted river water. *Ecological Engineering*, 133, pp. 167–176. https://doi.org/10.1016/j.ecoleng.2019.04.022
31. **Sharma, R., Vymazal, J. and Malaviya, P. (2021)** Application of floating treatment wetlands for stormwater runoff: a critical review with emphasis on heavy metals and nutrient removal. *Science of the Total Environment*, 777, 146044. https://doi.org/10.1016/j.scitotenv.2021.146044
32. **Sheoran, A.S. (2006)** Laboratory treatment of acid mine water using wetlands with emergent macrophytes (*Typhaangustata*). *International Journal of Mining, Reclamation and Environment*, 20(3), pp. 209–222. https://doi.org/10.1080/17480930600982753
33. **Solano, M.L., Soriano, P. and Ciria, M.P. (2004)** Constructed wetlands as a sustainable solution for wastewater treatment in small villages. *Biosystems Engineering*, 87(1), pp. 109–118. https://doi.org/10.1016/j.biosystemseng.2003.10.005
34. **Spangler, J.T., Sample, D.J., Fox, L.J., Albano, J.P. and White, S.A. (2019a)** Assessing nitrogen and phosphorus removal potential of five plant species in floating treatment wetlands receiving simulated nursery runoff. *Environmental Science and Pollution Research*, 26, pp. 5751–5768. https://doi.org/10.1007/s11356-018-3964-0
35. **Spangler, J.T., Sample, D.J., Fox, L.J., Owen, J.S. and White, S.A. (2019b)** Floating treatment wetlands for nutrient removal from agricultural runoff using two wetland species. *Ecological Engineering*, 127, pp. 468–479. https://doi.org/10.1016/j.ecoleng.2018.12.017
36. **Surujdeo-Maharaj, S., Alkins-Koo, M., Rostant, W., Maharaj, L., Lucas, F. and Yen, I.C. (2004)** Metal pollution considerations in integrated water resource management for Trinidad and Tobago. In: *Proceedings of the Caribbean Environmental Health Institute (CEHI) Conference*.
37. **WHO, UNEP and FAO (2006)***Guidelines for the safe use of wastewater, excreta and greywater*. 3rd edn, Volume II: Wastewater use in agriculture. Geneva: World Health Organization.
38. **Zhang, D.Q., Hua, T., Gersberg, R.M., Zhu, J., Ng, W.J. and Tan, S.K. (2013)** Carbamazepine and naproxen fate in wetland mesocosms planted with *Scirpusvalidus*. *Chemosphere*, 91(1), pp. 14–21. https://doi.org/10.1016/j.chemosphere.2012.11.018
39. **Zhang, W., Guan, A., Peng, Q., Qi, W. and Qu, J. (2023)** Microbe-mediated simultaneous nitrogen reduction and sulfamethoxazole removal in lab-scale constructed wetlands. *Water Research*, 242, 120233. https://doi.org/10.1016/j.watres.2023.120233
40. **Zhang, H., Huang, H., Chen, W., Zhang, Z., Li, H. and Li, J. (2024a)** Mechanistic insights into efficient PPCP removal using waste biological activated carbon for low-carbon

reutilization. *Chemical Engineering Journal*, 487, 150759. https://doi.org/10.1016/j.cej.2024.150759

41. **Zhang, S., Cui, L., Zhao, Y., Xie, H., Song, M., Wu, H., Hu, Z., Liang, S. and Zhang, J. (2024b)** Role of microplastics in sulfamethoxazole fate and antibiotic resistance gene transformation in vertical subsurface-flow constructed wetlands. *Journal of Hazardous Materials*, 465, 133222. https://doi.org/10.1016/j.jhazmat.2023.133222
42. **Zhuang, L.L., Li, M., Li, Y., Zhang, L., Xu, X., Wu, H., Liang, S., Su, C. and Zhang, J. (2022)** Performance and mechanisms of biochar-enhanced constructed wetlands for wastewater treatment. *Journal of Water Process Engineering*, 45, 102522. https://doi.org/10.1016/j.jwpe.2021.102522