

Pioneering Sustainable Hydro-Systems in the Caribbean: Renewable Energy Approaches to Wastewater Reuse and Irrigation in the Caroni River Basin, Trinidad and Tobago

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ABSTRACT

This study employs a mixed-methods research design to investigate effective approaches for quantifying the removal efficiencies of key water quality parameters (e.g., BOD-5, COD, TSS, NH₄-N, PO₄³⁻, E. coli) by varying geotextile membrane types and bio-filter media compositions within experimental rigs. The filter performance of the Biochar, Coated Chitosan on Coconut Shell Activated Carbon (CAC), Gravel and Sharp sand profile will be compared when treating reclaimed water (RW), conventional irrigation water (CW), and secondary effluent (SW) from a wastewater treatment plant (WWTP), using a Wastewater Reuse Prototype (WWR) to assess improvements in treatment performance, increased water supply, and reduced pollution from three (3) sources. This study will demonstrate how Vertical Flow Constructed Wetlands, planted with Phragmites Australis plant species, can be used for the treatment of municipal wastewater. The main objective of this study is to evaluate the system's efficiency in removing pollutants and facilitating nitrification. The previous research at the Guanapo Landfill Project Site demonstrated that specialised plants can slow down water to allow solids to settle, convert contaminants into less harmful substances and support microorganisms that filter and purify water. The treatment resulted in an environmentally acceptable effluent quality. The study will demonstrate how Solar Powered Automated Drip Irrigation (SPDI) system using a pump and solar panels for drip irrigation of Lettuce and Kale, can be used to quantify the water savings, energy consumption (kWh/day), and crop yield (e.g., biomass, marketable yield, water use efficiency) achieved by efficient irrigation. This research will assess Knowledge, Attitudes, Practices (KAP), and

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Willingness to Pay (WTP) to inform national standards for wastewater reuse. The study will explore the Water-Energy-Food nexus, focusing on the links between crop production risks, renewable energy, and the reuse of treated wastewater in agriculture. The final assessments will demonstrate that this innovative approach uses suitable technologies for safe water reclamation in agriculture, promoting environmentally safe and sustainable practices in the Caribbean.

INTRODUCTION

This study aims to investigate the risks and hazards associated with treated wastewater and agrochemicals, as well as to assess water and crop quality at the proposed site for the Orange Grove Food Crop Project in Tacarigua, Trinidad, West Indies.

The key Aims of the study are as follows:

- (i) To quantify the influence of geotextile membranes and bio-filter media on pollutant removal efficiency in experimental bio-filters.
- (ii) To determine the optimal, cost-effective configuration for a Vertical Flow Constructed Wetland (VFCW) system for treating decentralised domestic wastewater.
- (iii) To evaluate the efficiency of a Solar-Powered Automated Drip Irrigation (SPADI) system for enhancing wastewater reuse and water resources amplification for improved crop yield in lettuce and kale cultivation.

The key Objectives of the study are as follows:

- (i) To quantify the removal efficiencies of key water quality parameters (e.g., BOD-5, COD, TSS, NH₄-N, PO₄³⁻, E. coli) by varying geotextile membrane types and bio-filter media compositions within experimental bio-filter rigs, comparing their performance when treating Reclaimed Water (RW), Conventional Irrigation Water (CW), and Secondary Effluent (SW) from a Wastewater Treatment Plant (WWTP).
- (ii) To evaluate the treatment performance (e.g., BOD, COD, TSS, pathogen removal) and hydraulic conductivity of various Vertical Flow Constructed Wetland (VFCW) configurations, differing in media layering, depth, and plant species, to identify the most efficient and cost-effective design for on-site decentralised domestic wastewater treatment, comparing effluent quality against local discharge standards and its suitability for reuse as Reclaimed Water (RW), Conventional Irrigation Water (CW), or its original state as Secondary Effluent (SW).
- (iii) To quantify the water savings, energy consumption (kWh/day), and crop yield (e.g., biomass, marketable yield, water use efficiency) achieved by a Solar-Powered Automated Drip Irrigation (SPADI) system, in comparison to conventional irrigation methods, for the cultivation of lettuce (*Lactuca Sativa*) and kale (*Brassica Oleracea Var. Acephala*) under controlled experimental conditions.

The research will include a comprehensive literature review and will empirically explore the potential link between agricultural crop production risks and the reuse of treated wastewater for irrigation.

The project site, the Orange Grove Food Crop Project, 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, includes demonstration plots equipped with monitoring components, and has baseline soil property information available.

Lettuce (*Lactuca Sativa*) and Kale (*Brassica Oleracea Var. Acephala*) have been selected as the crop for this study due to their sensitivity to irrigation water quality issues. As the most commonly consumed raw vegetable, lettuce's leafy structure may protect pathogens from light and desiccation, promoting their persistence (Pettersen et al., 2001). The choice of this crop was also influenced by its growth rate, given that the total data collection timeline is eighteen (18) months.

This study will examine the water-energy-food 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.

LITERATURE REVIEW AND SPECIFIC WORK RELATED TO RESEARCH

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 (Pettersen et al., 2001; Eslamian, 2016), providing nutrients that minimise the need for synthetic fertilisers (Rawlins et al., 1998; Pedrero et al., 2010; Lyu et al., 2016), and generating higher crop yields compared to freshwater irrigation (Rawlins et al., 1998; Michetti et al., 2019). However, improper management of water reclamation can lead to negative consequences for the environment and human health (Lazarova et al., 2013; Eslamian, 2016). The most widely recognised risk is the potential introduction of pathogens into the food supply chain (Rawlins et al., 1998). Furthermore, increased salinity can adversely affect crops and soil quality (Pedrero, 2008; Pedrero et al., 2010), while phytotoxic elements can inhibit plant growth and reduce crop yields (Pettersen et al., 2001; Pedrero, 2008). High levels of sodicity can also deteriorate soil structure (Pedrero, 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 Volatilisation, where some contaminants transfer from water to air through evaporation. Findings of evaporative rates in water storage reservoirs in Trinidad and Tobago show that as temperatures rise due to climate change, water loss accelerates, posing a severe risk to water storage capacity and long-term irrigation water supply reliability. Findings from water evaporation studies were reported in the Journal of

the Association of Professional Engineers of Trinidad and Tobago, Volume 53, Number 2 (ISSN 1010 7924, October 2025) as follows:

Findings from Evaporation Studies:

- (i) **Temperature Increase:** Daily Maximum temperatures in T & T can reach 34.5 °C and are projected to rise by 1.5 °C every decade, reaching 42.9 °C by 2060.
- (ii) **Evaporation Rates:** Rising Temperatures directly increase evaporation rates. Forecasts show an average 94.8% increase in evaporation by 2060.
- (iii) **Reservoir Impacts:**
 - o Navet & Hillsborough: Highest projected evaporation increases (up to 78% Water Loss)
 - o Hollis: 48-72% evaporation increase
 - o Caroni Arena: Lowest Impact (23-34%, but still significant given its national importance).
- (iv) **Regression and Correlation Analysis:** Strong statistical correlation ($R^2 = 1$) between temperature, elevation and surface area confirms evaporation's sensitivity to climate change.
- (v) **Overall Trend:** As temperatures rise, water loss accelerates, posing a severe risk to reservoir capacity and long-term water supply reliability.

METHODOLOGY

WWR-Prototype Design Experimental Set-up

The Caribbean case studies informed the methodology for researching wastewater quality management, employing a mixed methods approach with quantitative and qualitative techniques. Two (2) experimental setups, Vertical Flow Constructed Wetland and Gravity Bio-Filter systems, were tested using two (2) crops, Lettuce and Kale. Three (3) types of influent water were used: Reclaimed Water (RW) from the WWR-prototype, Conventional Irrigation Water (CW), and Secondary Effluent (SW) from the Trincity WWTP, with RW produced by treating SW. The WWR-Prototype incorporates three (3) storage tanks, one (1) of which is for reclaimed wastewater, featuring layers of granular material and geotextile membranes engineered to gather treated wastewater (SW). The laboratory experimental setup facilitated all the flow and water-quality measurements. Three (3) experimental reclaimed wastewater storage tanks were used to evaluate the water quality of both the inflow (SW) and outflow (RW). The storage tanks were designed with three (3) variations:

- (i) Without a geotextile membrane,
- (ii) With an upper geotextile membrane, and
- (iii) With both upper and lower geotextile membranes. Weekly monitoring of various water quality parameters, including nutrients, biochemical oxygen demand, chemical oxygen demand, and suspended solids, was conducted.

Data collection and weekly laboratory analyses primarily utilised water quality meters and a spectrophotometer, respectively. The experimental surveys aimed to assess contaminant retention in the WWR-prototype layers and evaluate the long-term effectiveness of geotextile membranes and filters in removing contaminant accumulation. The water quality results would indicate the efficacy of the system's infiltration technologies in removing typical contaminants from the Secondary Effluent (SW) obtained from a Wastewater Treatment Plant (WWTP). The system features a permeable geotextile membrane within the WWR-Prototype situated in a storage tank.

The system also included a cutting-edge compact combination of water treatment technologies based on filtration through a biochar/chitosan/gravel profile. Chitosan, a natural biopolymer, is derived from the deacetylation of chitin, which is found in marine organisms, such as crustaceans (e.g., crabs, shrimp, and lobsters) and insects, as well as in the cell walls of fungi. Biochar produced through biomass pyrolysis possesses numerous exchangeable cations on its surface, such as alkali or alkaline earth metals (Na, K, Mg, Ca), which can be substituted by heavy metal ions during sorption.

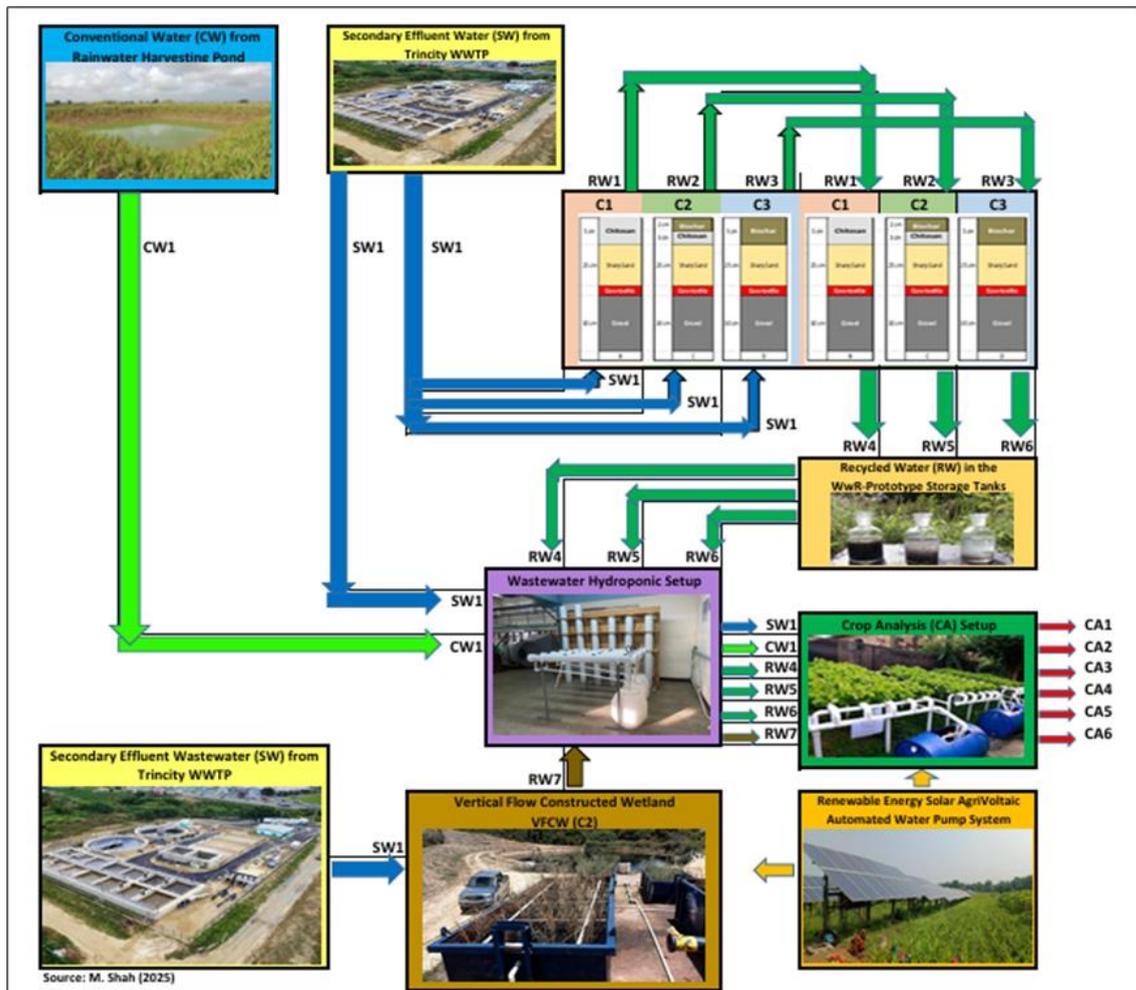


Fig. 1. A Flow Chart illustrating the Experimental Setup Methodology

Source: Authors (2025)

Gravity Bio-Filters

The Gravity Flow Bio-filter systems were constructed using plastic water tanks pipes of dimensions 350 mm × 350 mm × 780 mm (Length × Width × Depth).

Geotextile Membranes

Geotextile membranes are porous fabrics used in agriculture, made from natural materials such as jute and coir. They are eco-friendly, biodegradable, and a sustainable choice.

Crop Experimental Set-up

The cultivation of lettuce (*Lactuca Sativa*) and Kale (*Brassica Oleracea Var. Acephala*) is scheduled to occur over a 90-day period spanning from October to December 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 location 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 (Rawlins et al., 1998). 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 (Pettersen et al., 2001).

Irrigation Water Sources and Methods

The irrigation process utilised three (3) 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: Caroni River (88.7%), Macoya River (3.0%), Dinsley River (6.7%), and Tantrill River (1.6%). CW are mainly used for agronomic quality control owing to their suitable salinity levels. SW was obtained from the Trincity WWTP after undergoing treatment involving pre-treatment steps, double-stage activated sludge with extended aeration, and secondary clarification. The experiment combined three (3) water types (RW, CW, and SW) with two (2) types of leafy vegetable crops, namely Lettuce and Kale (L and K), resulting in six (6) treatments: RW-L, RW-K, CW-L, CW-K, SW-L, and SW-SK each with four (4) lettuce and kale crop replicates. Using a randomised design, 144 lettuces and kale plants were planted per treatment plot (12 plants/m² spacing) on ridges, totalling 864 lettuce and kale plants in the entire area (See Figure 2).

Irrigation Water Quality Analyses

Physicochemical analyses will be conducted for the different irrigation water types. Bi-weekly grab samples (eight (8) in total) were collected during the experimental period using clean, non-sterile bottles (not for microbiological analyses). The bottles were then rinsed and filled with water before collection. After transportation to the laboratory, the samples were stored at Five Degrees Celsius (5°C) prior to processing.

A closed hydroponic system was set up which saves more water and fertilisers than an open system. The three (3) types of water CW, SW and the recycled treated wastewater (RW) is pumped through the growing zone and flows over the lettuce plant roots. The water-saving effect of this system has been confirmed by many studies. One (1) potential problem of closed hydroponic systems may be the accumulation of salt ions, mainly sodium (Na) and chlorine (Cl). The increase in salt concentration leads to a decrease in plant photosynthesis and transpiration rates, a reduction in plant weight, and an apparent toxicity effect caused by chlorine (Cl).

Wastewater quality parameters measured at the UWI Laboratory include the physicochemical parameters such as pH, Conductivity, Total Dissolved Solids (TDS), Dissolved Oxygen (DO) and Temperature.

The chemical parameters measured include Nitrate, Ammonia, Phosphorus, Potassium, Chloride and COD while the bacteriological parameter measured was Faecal Coliform. The above parameters were selected based on their importance in wastewater treatment and reuse for irrigation.

Temperature and pH which are among the physicochemical parameters can help to understand the operating conditions of the system while TDS, Conductivity and DO can provide the primary indication of the chemical constituents available in the wastewater.

Nitrate, Potassium and Phosphorus are the essential nutrients for crops growth, and the interest of the study was to know how much is available in the final effluent and become available for crop nourishment. Ammonia was measured because it has toxic nature such that when there is high levels of Ammonia biological life can be affected, and the performance of the treatment system be severely affected.

COD was measured to help quantify the amount of organic loading as high organic organics depletes oxygen in the receiving environment and it is desired that the final effluent be of low organic loading.

Faecal Coliform is used as an indicator for faecal pollution therefore it was used to portray a picture of the biological pollution loading.

The physicochemical parameters were measured on site. DO was measured using the DO meter (HI 9146), pH was measured using a field pH meter and was cross checked again in the laboratory using a bench pH meter. TDS, Conductivity and Temperature were measured using the waterproof Conductivity Meter (HACH SensION5).

Chemical parameters were measured at the UWI Laboratory. The analysis of the COD was done using the closed reflux titrimetric method, Nitrate using the Cadmium Reduction Method, Phosphate using the Ascorbic Acid standard method and Potassium using the Tetra-phenylborate Method (APHA, 1999).

The Spectrophotometer DR 2700 was used for all the colorimetric methods. Faecal Coliform were analysed using the Membrane Filtration Technique. The appropriate sample treatments such as sample filtration and dilution using dilution water were done before incubating at temperature of 44.5 C.

Crop Quality Analyses (Lettuce and Kale)

For analysing agronomic quality, microbial analyses are performed whereby sampling of lettuces are performed at their growth stage 49, according to the BBCH scale, when the produce reaches commercial size. Each sample consists of a whole lettuce head cut from its base, removing traces of soil. To analyse

commercial weight, total N and C concentrations, macronutrients, micronutrients, and metals, three (3) lettuces per treatment are randomly sampled during two (2) consecutive days, thus 36 lettuces in total. Fresh (whole lettuce) and commercial (cleaned lettuce, without outer leaves) weights will be 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 are dried for at least two (2) days at 65 Degrees Celsius to measure dry weight.

The percentage of water content in lettuces is calculated based on fresh and dry weight values. To analyse C concentrations, macronutrients (total N, NO_3^- , PO_4^{3-} , K, Ca, Mg), micronutrients (Fe et al.), phytotoxic elements (B, Cl^- , Na) and metals, lettuce leaves undergo a cleaning preparation process. This process consists 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 are then drained by leaving them on a filter paper. Later, they are oven-dried at 65 Degrees Celsius for at least two (2) days. Dried samples are blended and digested in nitric-perchloric acid (2:1).

Replicate samples of 25 g are also digested in Aqua Regia acid HCl/H NO_3 . Total N and C concentrations are analysed with an automatic micro-analyser Flash EA 1112 Series (Flash et al.) and Leco Truspec (Sant Joseph, USA). Elements and anions are assessed by mass spectrometry, using an Inductively Coupled Plasma spectrometer (ICP-ICAP 6500 DUO Thermo, England), and by ion chromatography, using a chromatograph (Metrohm, Switzerland). Samples for both spectrometry and chromatography are diluted using a standard leaf-to-distilled-water ratio of 1:2.5. Sampling and analyses comply with the standard methods in the Laboratory guide for conducting soil tests and plant analysis (Peters Everson & Vivian Joseph, 2015).

Ten (10) lettuce samples are taken per treatment per day for three (3) consecutive days, hence 864 lettuces in total. Each sample consists of a whole lettuce head cut from its base. Traces of soil, as well as outer leaves in poor shape, are removed. Harvested lettuces are aseptically stored inside individual food-grade plastic bags and transported immediately to the lab for analysis. Once in the lab, each lettuce head is chopped aseptically, and a homogeneous sample of 25 g is picked up and stored in a Stomacher® bag without a filter. The 25 g sample is then diluted 1:5 in buffered peptone water (BPW, 20 g L^{-1} concentration) and mixed in an automatic blender.

To assess culturable E. coli, the sample is poured into Chromocult coliform agar (Merck et al.) directly from the bag. After incubating plates at 37 Degrees Celsius for 24 hours, colonies in dark blue-violet colour are considered positive for E. coli. After E. coli plating, 125 mL of BPW (20 g L^{-1}) is added to the stomacher bags, which is then incubated for 24 hours at 37 Degrees Celsius for enrichment. After the incubation, 7 mL of the E. coli sample is transferred to sterile tubes and mixed with glycerol (3 mL). Tubes are kept at minus (-20 °C) until DNA extraction is performed. DNA extraction, detection by RT-PCR and confirmation of the presence of pathogenic bacteria is performed.

Agronomic Quality Methodology

- (i) Field Sampling: Soil and plant samples were collected from different parts of the field.
- (ii) Laboratory Analysis: Soil was analysed for nutrient content, pH, organic matter, and other properties
- (iii) Plant Analysis: Plant health was assessed for growth parameters, and yield.

- (iv) Pest and Disease Assessment: Crop was checked for signs of pests and diseases.
- (v) Data Interpretation: Agronomic data were used to make decisions on fertilisation, irrigation, and pest control.

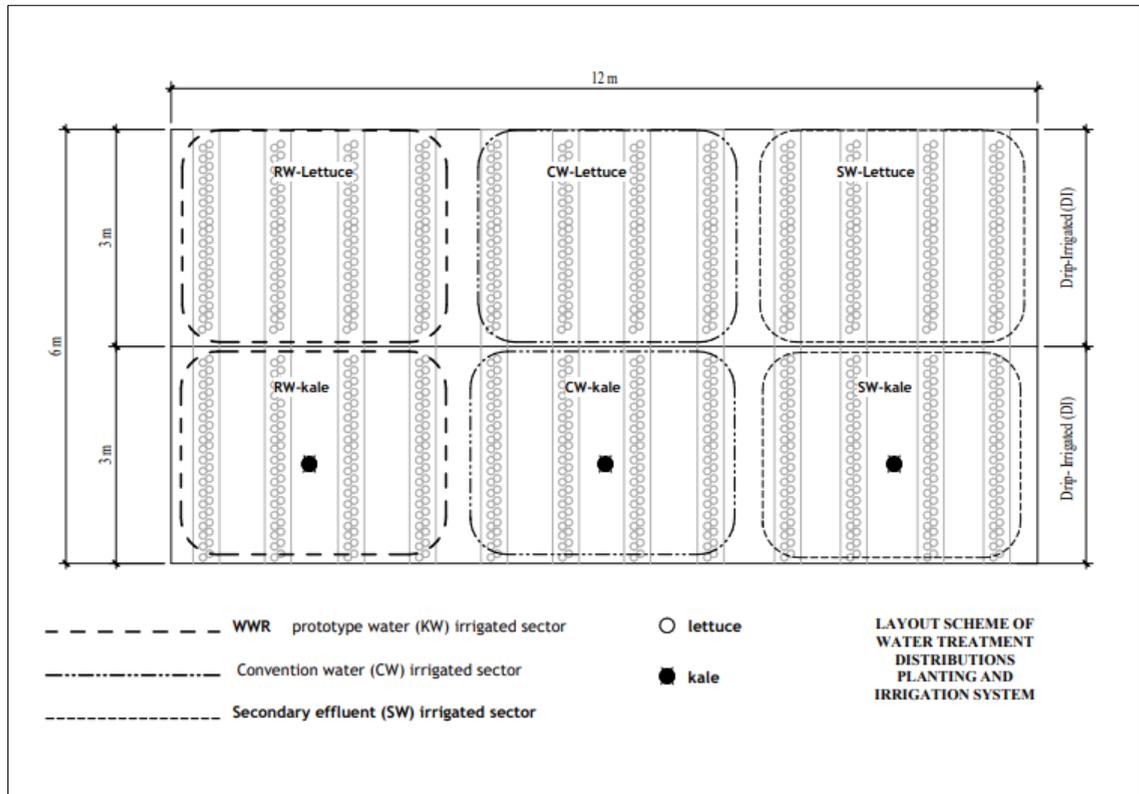


Fig. 2. Schematic Layout of Planting and Irrigation Distribution in the Field

Source: Authors (2025)

Vertical Flow Constructed Wetland System

The vertical flow-constructed wetland system experimental setup wetlands tested two (2) crop types (Lettuce and Kale) using three (3) 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 m² 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/m² using seedlings or rhizomes (See Figure 3).

The 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 utilise physical, biological, and chemical mechanisms to remove pollutants. VFCW require proper lining and filter material.

Design Specifications of Vertical Flow Constructed Wetland and Design Guidelines for Efficient Wastewater Treatment:

- (i) Depth: 0.5 to 1 meter.
- (ii) Surface Area: Based on wastewater volume and treatment goals.
- (iii) Flow Rate: Ensure adequate contact time with filter media.
- (iv) Plant Selection: Use deep-rooted wetland plants for permeability and microbial support.
- (v) Maintenance Access: Include access points for solid removal and vegetation management.

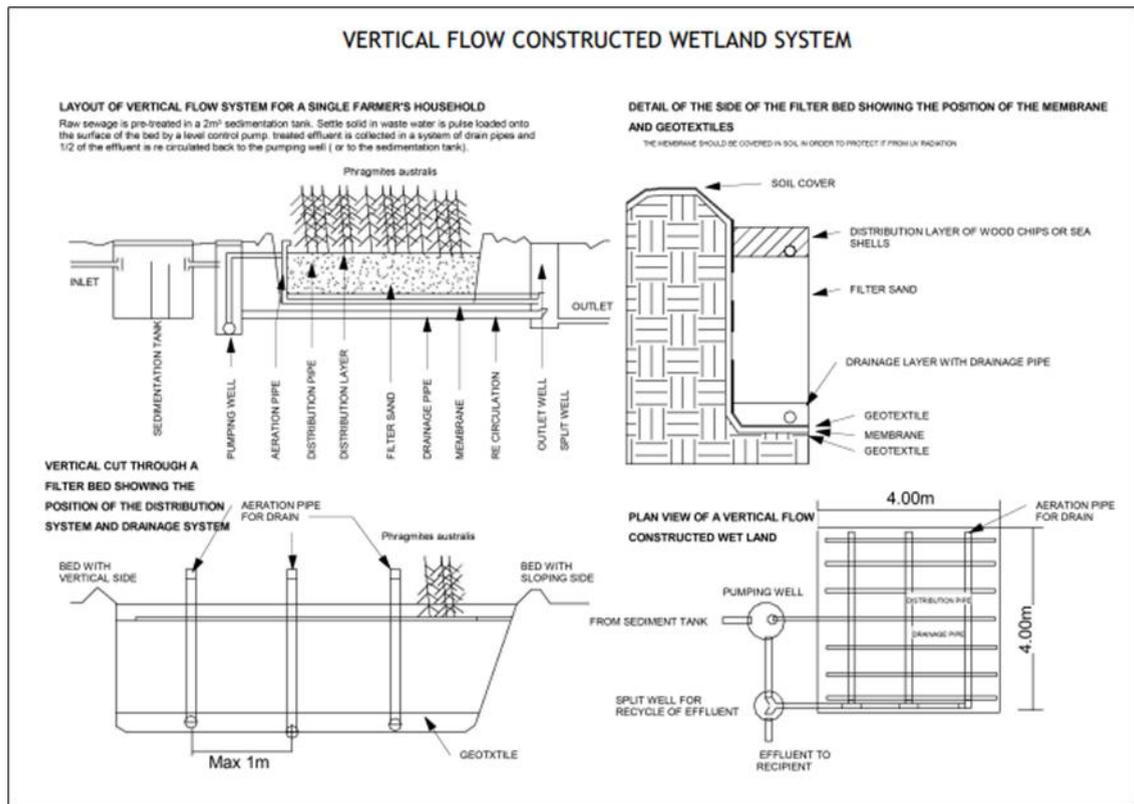


Fig. 3. Schematic Diagram of Vertical Flow Constructed Wetland System

Source: Authors (2025)

Recommendations for Enhanced Efficiency of Horizontal Flow Constructed Wetland (HFCW)

- (i) Horizontal Subsurface Flow (HSSF) systems require coarse media (10–25mm) to enhance flow and minimise clogging. Hybrid systems benefit from a mix of finer (4–10mm) and coarse substrates (10–40mm) for improved nitrification (See Figure 4).
- (ii) Longer Hydraulic Retention Time (HRT) improves nutrient removal; hybrids are effective at four (4) days, while HSSF needs at least three (3).
- (iii) Loading Frequency and Distribution: Intermittent loading (4–6 times daily) increases oxygenation in hybrids, and even 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 reducing clogging; future designs should prioritise balanced flow inlets.

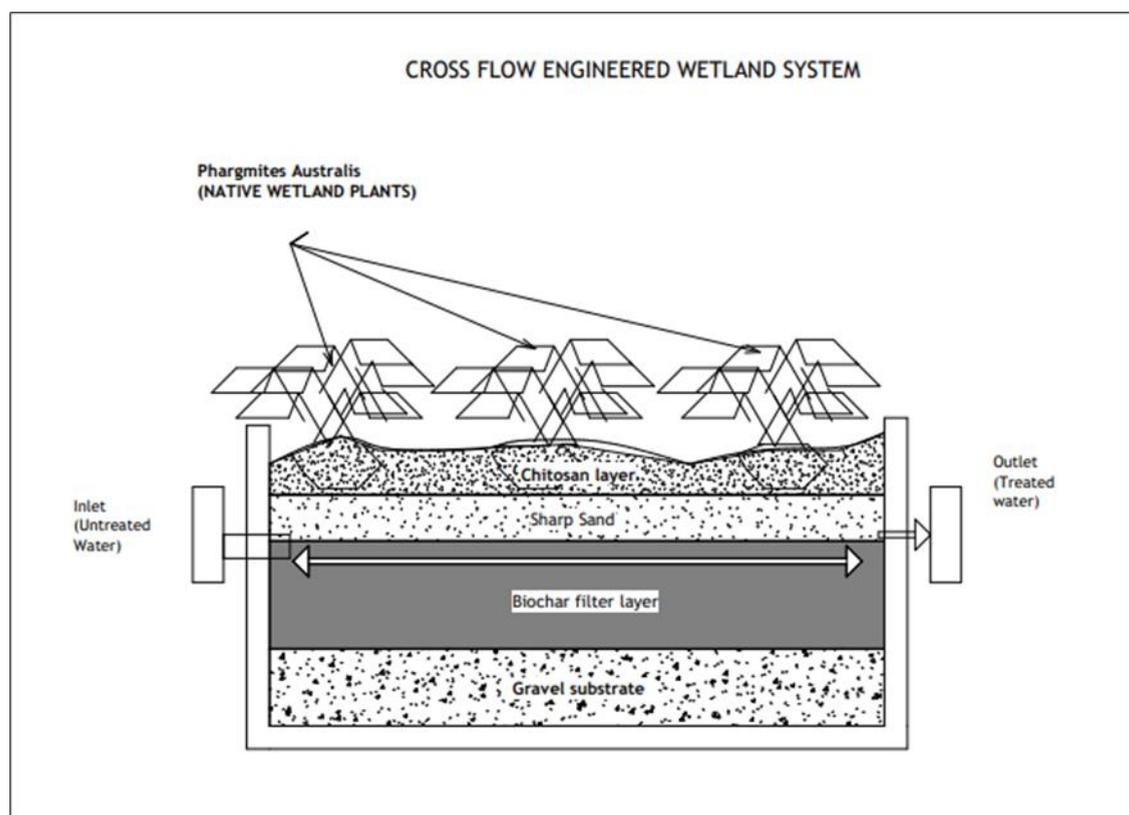


Fig. 4. Experimental Setup of Horizontal (Cross) Flow Constructed Wetland System – Planted Horizontal Flow Constructed Wetland Setup

Source: Authors (2025)

Solar Powered Automated Pump System for Drip Irrigation

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

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 around 40 m³ 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 (8) 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 m³ of water per day is sufficient to irrigate up to one (1) hectare of land planted with regular crops.

The aim was to find an affordable pump and minimise costs by avoiding using batteries. By using a DC pump the cost of DC/AC conversion was avoided. The drawback is that DC motors have a shorter life than AC motors. Marine pumps were found to be a good choice, but many of them are designed only for low heads. The actual pump can deliver around 15 m³/hour or 4 litres/second at zero head. It can work at 5–6 m head, but then the flow rate is lower albeit sufficient for the purpose. In this case, the motor is assumed to have a life of around one (1) year. However, the profit from the irrigation could pay for the replacement of the motor. Altogether, the pumping system cost was less than 1,000 USD. No electronic controllers were used - only a simple circuit breaker. The pump can irrigate around half a hectare (=5000 m²). A flow rate of 4 m³/hour for six (6) hours will provide almost 50 m³/hectare/day.

Capital Cost

In a renewable system the complete solar PV system consists of several elements to be connected with the solar modules. The solar cells usually represent the highest capital cost. The total cost for the system includes inverters, mounting structures and electric circuits. An important aspect is the cost of energy storage, in many cases a battery system. Soft costs include a control system for power management and labour costs for the installation.

Supply and installation of 3.0 kW Solar Photovoltaic Panel (Monocrystalline) system array. Installation requires mounting and securing to metal structures on the ground of adequate strength and design to withstand a load of modules and high wind velocities of up to 150 km/hour. Provision of 6kW Pure Sine Wave Inverter and 6 KW Solar Hybrid System Split Phase 120V/ 240V, 60 HZ, 5.1 kW Lithium-Ion Battery Bank Controller System (Deep Cycle Lead Acid (AGM) type with 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.

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 was gathered from n respondents throughout Trinidad and Tobago, using convenience sampling. The sample size, n, was determined using the Kish formula. 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.

$$n = n^1 / [1 + (n^1 / N)] \quad (1)$$

To achieve a 95% confidence level, Kish's formula was used to calculate the sample size as described by Assaf & 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 (See Table 1):

Table 1. Showing how Kish's formula was used to calculate the sample size

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

N = Total number of populations,

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 ($S=0.5$, $V=0.06$).

Source: Authors (2025)

RESULTS

Irrigation Water

The water reclamation system of the WWR-prototype is expected to obtain removal efficiencies for EC, SAR, turbidity, and TSS, respectively. Removal efficiencies for nutrients of agronomic interest, i.e. NO_3^- , PO_4^{3-} and K, removed from SW would be determined. 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 will be determined whether under or over the detection limit. The presence of culturable E. coli will be assessed for significant differences among the different types of irrigation water. If the concentrations surpassed the threshold limits, the water sample would not be considered a suitable irrigation water source unless other preventive measures are taken. In this regard, storage and conveyance of CW through open-air reservoirs and canals, respectively, render this water source prone to contamination before it reaches the end user (See Table 2 and Table 3).

Table 2. 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 ($\text{NO}_3\text{-N}$)	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%

Source: Authors (2025)

Crop Quality (Lettuce and Kale)

The water content of lettuces in the six (6) treatments should fall within the 93.0%—94.9% range, thus not presenting significant differences. To prevent inaccuracies, irrigation of the different waters will be evenly kept throughout the experiment for the drip irrigation (DI) system, according to its technical specifications. However, all treatments should comply with the commercial minimum weight of 100 g for Lettuces and Kale (classes I and II) grown under protection (UNECE, 2012; OECD, 2002).

The research study involves Precision Irrigation Systems (Drip Irrigation) that optimise water use and minimise runoff or over-application. This ensures treated wastewater is used efficiently and enhances soil health, reducing pollution risks. Water requirement for vegetable crop production on one (1) hectare of agricultural land is 70 m³/day/ha (with an Average Irrigation Water requirement of 7 mm/day), with variations depending on season, temperature and crop growth stage.

To assess the quality of lettuces, physicochemical and microbiological characteristics were compared against selected standards. Commercial weights of lettuces were compared against European commercial standards (OECD,2002; UNECE,2012), NO₃⁻ concentrations against the European Commission Regulation No 1881/2006 (European Commission, 2006), and macronutrients and micronutrients against optimum ranges and phytotoxic thresholds found in related literature (Hartz et al., 2007; Marschner & Marschner, 2012).

Water content in lettuces amongst the six (6) treatments were in the range of 93.0% - 94.9% (data not shown), thus not presenting significant differences. To prevent inaccuracies, irrigation of the different

waters was evenly kept throughout the experiment for the CW, SW and RW systems. All treatments complied with the commercial minimum weight of 100 g for romaine lettuces (classes I and II) grown under protection (UNECE, 2012; OECD, 2002).

Vertical Flow Constructed Wetland System

Table 3. Performance Data (mean +1 S.D.) of some Single House Vertical Flow Constructed Wetland

SYSTEM	PARAMETER	INLET	OUTLET	PERCENTAGE REMOVAL EFFICIENCY (%)
Vertical Flow System (without Circulation)	TSS	85+28	8+3	91
	BOD	254+123	19+4	92
	NH4-N	105+45	23+17	78
	NO2 + NO3-N	<0.1	40+13	-
	Total N	125+51	72+28	43
	Total P	17.2+7.0	13.0+6.6	25
Vertical Flow System (with 100% Recirculation)	TSS	68+22	3+1	96
	BOD	100+35	11+3	89
	NH4-N	45+13	7+1	85
	NO2 + NO3-N	0.13+0.0	36+4	-
	Total N	0	44+5	23
	Total P	57+13	5.7+1.2	0
		5.2+1.7		

NB: The inlet samples were taken 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 persons, and a farming acreage of 355 acres.

Source: Authors (2025)

Statistical Analysis

The statistical analyses of results will be obtained and approaches suitable for assessing the performance of various materials for allowing good removal of typical pollutants in the treated wastewater effluent will be determined. Google Survey Forms will be distributed online to gather insights into current practices and challenges of the use of wastewater in agriculture. The analysis of the data obtained will reveal how innovative, data-driven techniques can contribute to sustainable agriculture. Statistical Analyses will be conducted using SPSS Software (Version 19).

DISCUSSION

Environmental Benefits

The treated wastewater supply will promote environmental sustainability by connecting rural and urban areas, reducing pollutant discharge, and minimising groundwater pollution while effectively utilising nutrients found in wastewater. The development of a management plan for the Caroni River Basin (CRB) aims to protect ecological integrity and conserve biodiversity through sustainable resource use, favouring a participatory approach instead of top-down legislation. Additionally, implementing vertical flow constructed wetlands will help mitigate stormwater runoff, while educating farmers on proper system management will address health and environmental risks. Sustainable practices such as drip irrigation will

reduce water usage, enhance carbon sequestration in agricultural areas, and maintain water quality according to crop needs, thereby supporting the livelihoods of local communities.

One (1) benefit of agricultural wastewater reuse is the avoided cost of extracting groundwater resources. In this regard, it is worth noting that the energy required to pump groundwater can represent up to 65% of the costs of irrigation activities.

Additionally, the nutrients naturally present in wastewater allow savings on fertiliser expenses to be realised, thus ensuring a closed and environmentally favourable nutrient cycle that avoids the indirect return of macro- (especially nitrogen and phosphorous) and microelements to water bodies. Depending on the nutrients, wastewater may be a potential source of macro- (N, P and K) and micronutrients (Ca, Mg, B, Mg, Fe, Mn or Zn). Indeed, wastewater reuse has been proven to improve crop yield and result in the reduced use of fertilisers in agriculture. Therefore, eutrophication conditions in water bodies would be reduced, as would the expenses for agrochemicals used by farmers.

The prevention of water pollution would be another benefit associated with wastewater reuse in agriculture. A decrease in wastewater discharge helps improve the source quality of receiving water bodies. Moreover, groundwater reservoirs are preserved, as agricultural wastewater reuse recharges these sources with higher-quality water. Additionally, an increased use of wastewater could contribute to the installation and optimisation of treatment facilities to produce effluent of a desired quality for irrigation purposes, representing an economic benefit to sanitation projects. In those areas where climatic and geographic characteristics allow, low-cost wastewater treatment systems might also be a viable option, achieved by using specific technological options that fulfil the objective of agricultural wastewater reuse.

Social and Community Benefits

Regulatory and institutional improvements, alongside awareness campaigns, will empower the population regarding drought management, enhancing 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 while 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.

On the basis of regulatory aspects, agricultural wastewater reuse can contribute to the justification of suitable investment policies and financing mechanisms for pollution control and prevention.

Economic Benefits

The treated wastewater will 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 fertilisers, and lowering water treatment costs for downstream users.

An implicit economic benefit of agricultural wastewater reuse is the valuation of the 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 searching for water sources using more expensive means.

Legal Benefits

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

- (i) Policy and Administrative Measures.
- (ii) Policy Development Driving Forces.
- (iii) Legislation: Water Pollution Regulation, Miscellaneous Water-Related Laws.
- (iv) Occupational Safety and Health Act, Role and Function of the Pesticides and Toxic.
- (v) Chemicals Control Board, Obligations under International Instruments.
- (vi) Development of Safe and Effective Wastewater Reuse and Irrigation Water Management.
- (vii) Development of a GIS-Based Water and Wastewater Management Assessment Model.

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

Irrigation Water Quality

The presence of culturable *E. coli* will be assessed for significant differences among the different types of irrigation water. If the concentrations surpass the threshold limits, the water sample would not be considered a suitable irrigation water source unless other preventive measures are taken. According to previous research studies, storage and conveyance of CW through open-air reservoirs and canals, respectively, render this water source prone to contamination before reaching the end user, hence the presence of *E. coli* concentrations.

Studies indicate that grey water containing detergents inhibits the reclamation process, causing cloudiness, colour changes, and excessive bubbles, which reduces its acceptability for indoor uses. Public perception of chemical treatments for grey water is negative; thus, physical treatments like adsorption, filtration, or ion exchange using low-cost materials are recommended to remove chemicals from cleaning and personal care products. This approach eliminates the need for chemical treatments and increases public willingness to recycle grey water due to lower costs and quicker payback periods.

Materials such as charcoal, coconut shell, chitosan, feldspar, kaolinite, alumina, bentonite, and pulverised fuel ash are promising for grey water reclamation. Low-cost material treatments can serve as polishing units in the final stage or as pre-treatment units to protect biological treatment systems from detergent damage, ensuring efficient system operation. The microorganisms in biological treatment can be destroyed by the detergent characteristics in grey water. But when low-cost materials are used as a pre-treatment (adsorption/ion exchange unit), then the detergent characteristics can be removed before they enter the biological system, thereby protecting the microorganisms and allowing the system to work efficiently.

Crop Quality (Lettuce and Kale)

To assess the quality of lettuce and kale, physicochemical and microbiological characteristics will be compared against selected standards and macronutrients and micronutrients against optimum ranges and phytotoxic thresholds found in related literature (Hartz et al., 2007; Marschner & Marschner, 2012). Water content in lettuce and kale amongst the six (6) treatments should fall in the 93.0%- 94.9% range, thus not presenting significant differences. 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).

Pollution parameters evaluated were faecal coliforms and helminth eggs. The water quality was monitored during three (3) months and their concentration levels ranged from 3 to 4 log units of faecal coliforms in 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 7×10^2 and 1.8×10^3 in 10 g and the 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 its development in the risk assessment for possible infections caused by helminths and *E. coli* (See Figure 5).

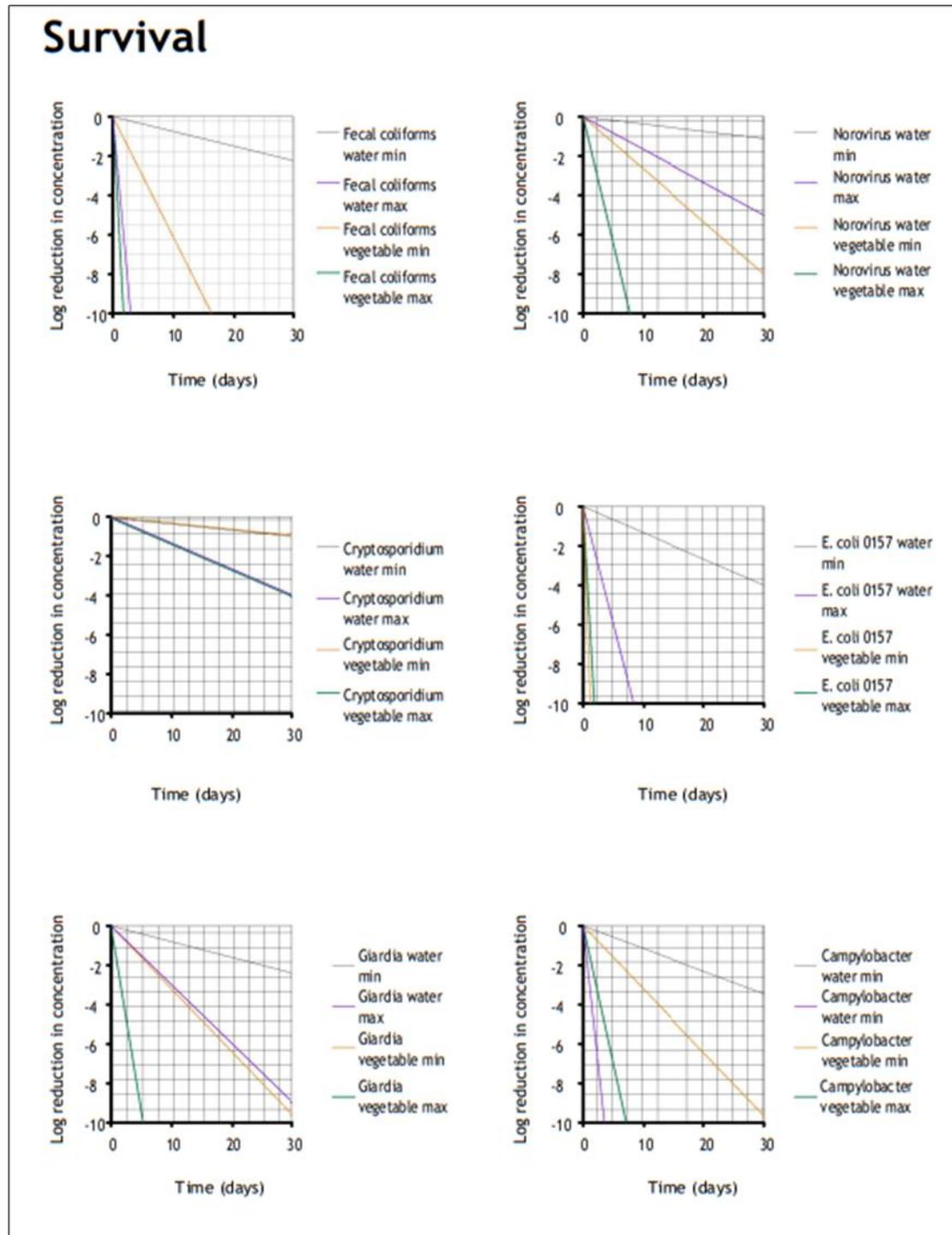


Fig. 5. Modelled Survival Rates in Water and on Vegetables

Source: Authors (2025)

Statistical Analysis

Analysis of the results is determined after performing Statistical Analyses using the SPSS Software, Version 19. The statistical distribution would allow a choice of focus to determine suitability for wastewater reuse. It will also present gaps where innovation can be achieved. Wastewater reuse in the agricultural sector possesses economic benefits that can improve farmers' livelihoods. Jimenez et al. (2008) 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. Moreover, spatial requirements for the facilities may be beyond the capacity of small islands (Bunting & Edwards, 2018). Peters Everson & Vivian Joseph (2015) proposed that hydroponics can mitigate the adverse consequences of wastewater reuse in agriculture.

Ethical Consideration

Secondary data would be carefully gathered as a reference for the research instruments to ensure their validity. Proper citations will acknowledge the contributions of related studies, avoiding credit appropriation. Signed consent letters will ensure voluntary respondent participation with a clear understanding of the study's purpose and methods. Data collection will maintain accuracy and reliability, with clear objectives and standardised instruments, free from bias or conflicts of interest. Privacy and confidentiality will be ensured through Non-Disclosure Agreements (NDA) and anonymisation techniques, safeguarding sensitive data. The research will be conducted at respondents' convenience, online or face-to-face, considering COVID-19 protocols. Ethical considerations will adhere to company policies and permits, aiming to positively impact sustainable water utilisation practices.

CONCLUSION

The WWR-prototype reclamation system investigated in this research is expected to effectively tackle 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 effluent. 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, represent 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 refinement of the prototype reclamation system to meet specific requirements. This strategy will ensure efficient utilisation of valuable plant nutrients while maintaining environmental compliance and mitigating risks in agricultural production. This study aims to stimulate the development of initiatives for the nationwide adoption of wastewater reclamation schemes for agricultural irrigation and to enhance related policies and procedures. Expected outcomes and impact: Development of innovative, nature-based treatment systems that can be scaled up and adapted across a range of contexts; Demonstration of resource recovery to promote circular economy models in agriculture; Generation of new scientific knowledge on ecosystem functioning in engineered environments; Policy recommendations to support the regulation and adoption of sustainable treatment practices; Capacity building in participating institutions and communities on ecological engineering for water management.

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CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

AUTHORS' CONTRIBUTIONS

The research was carried out by Ms. Michelle Shah wrote and revised the article. Ms. Shah conceptualised the central research idea and provided the theoretical framework. The research study was designed in collaboration with Professor Kiran Tota-Maharaj and Professor Hazi Azamathulla, who also supervised the research progress. Both Professors anchored the review, made revisions and approved the article submission.

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