Renewable Energy Approach for Wastewater Reuse in Horizontal Flow Constructed Wetlands and Solar Powered Drip Irrigation Systems in the Caribbean: A Case Study in the Caroni River Basin, Trinidad and Tobago, West Indies

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Abstract

Water and wastewater management is a vital topic that commands attention and action through various initiatives, including reuse, recycling, reclamation, and restoration. These strategies are essential for promoting responsible water utilisation, treatment, and disposal. We have made significant strides in establishing a national standard for wastewater reuse, as demonstrated by the Cabinet-approved National Voluntary Wastewater Reuse Standard TTS 664-2022. In response to the anticipated rise in irrigation demand driven by agricultural needs, this study will rigorously evaluate effective approaches using permeable geotextile materials and filter media, including Coated Chitosan (CS), Coconut Shell Activated Carbon (CAC), biochar-based filters, and Construction Waste Gravel. The study aims to create a Wastewater Reuse Prototype (WWR) for evaluating wastewater treatment efficiency and significantly reducing water pollution. This research will showcase the application of vertical-flow constructed wetlands, utilising Phragmite Australis, for treating municipal wastewater. The main goal is to comprehensively assess the system's ability to remove pollutants and facilitate nitrification. A solar-powered automated drip irrigation (SPDI) system will be introduced and designed for watering lettuce (Lactuca sativa) and kale (Brassica oleracea var. acephala) crops. Conclusive evaluations will confirm that the employed technologies are suitable for water reclamation in agricultural applications. These approaches will be supplemented with appropriate irrigation methods to reach environmentally safe and sustainable objectives. Our study will also include extensive analyses of Knowledge, Attitudes and Practices (KAP) and Willingness to Pay (WTP) to bolster the national voluntary standard for wastewater reuse and guide the implementation of effective strategies for treated wastewater and water management.

INTRODUCTION

This study aims to investigate the risks and hazards associated with treated wastewater and agrochemicals, as well as to test water and crop quality at the proposed site for the Orange Grove Food Crop Project in Tacarigua, Trinidad, West Indies. Aim 1: To quantify the influence of geotextile membranes and bio-filter media on pollutant removal efficiency in experimental bio-filters. Aim 2: To determine the optimal, cost-effective configuration for a vertical flow constructed wetland (VFCW) system for treating decentralised domestic wastewater. Aim 3: 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.

Objective 1: To quantify the removal efficiencies of key water quality parameters (e.g., BOD-5, COD, TSS, NH4-N, PO4 {3-}, 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).

Objective 2: To evaluate the treatment performance (e.g., BOD-5, 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).

Objective 3: 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 methodology, will encompass a comprehensive literature review and empirically investigate the potential connection 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 study crops 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 (Petterson et al., 2001). The choice of these crops was also influenced by their 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. The study 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.

This research addresses the pressing nexus of water scarcity, environmental sustainability, and agricultural resilience, particularly relevant for Small Island Developing States (SIDS) like Trinidad and Tobago. The escalating impacts of climate change, manifest in unpredictable rainfall patterns and prolonged droughts, underscore the urgent need for innovative, decentralised water management and efficient irrigation strategies. This proposal outlines a sustainable pathway by integrating renewable energy-driven wastewater reuse systems, directly contributing to national climate adaptation strategies and global sustainable development goals. This proposal is driven by a commitment to fostering agricultural resilience and environmental sustainability through the development and rigorous evaluation of innovative, context-specific water management technologies. The findings will provide actionable insights for practitioners, policymakers, and communities in the Caribbean and other regions facing similar environmental and socio-economic challenges.

The originality of this research is underscored by several synergistic and novel contributions:

1. Optimised Bio-filter Performance via Novel Media Integration: This study uniquely quantifies the enhanced pollutant removal efficiencies (including BOD-5, COD, TSS, and specific nutrients) achieved by incorporating geotextile membranes and various bio-filter media compositions within experimental bio-filter rigs. This approach aims to identify configurations capable of consistently treating diverse water sources (reclaimed water, conventional irrigation water, and secondary WWTP effluent) to a quality suitable for agricultural reuse, a critical step beyond conventional filtration.

2. Context-Specific Vertical Flow Constructed Wetland (VFCW) System Optimisation: Focusing on the distinct environmental and socio-economic context of the Caribbean, this research will determine the optimal, cost-effective VFCW configurations for on-site decentralised domestic wastewater treatment. By systematically investigating parameters such as media layering, depth, and plant species, the study will provide critical, empirically-derived design guidelines directly applicable to small-holder farming communities, thereby addressing a significant gap in locally tailored wastewater management solutions.

3. Demonstrating Water-Energy-Food Nexus through SPADI System Efficiency: The research comprehensively evaluates the efficiency of a solar-powered automated drip irrigation (SPADI) system. Beyond conventional energy savings, the study will quantify the precise water savings (e.g., volumetric reduction, water use efficiency metrics) and the tangible increase in crop yield (biomass and marketable produce) for lettuce and kale cultivation. This direct, quantitative demonstration of SPADI's benefits offers a scalable solution to reduce operational costs, lower carbon footprints, and enhance agricultural productivity in water-stressed regions.

4. Integrated Water Quality Assessment and System Interoperability: This proposal moves beyond isolated component testing by employing a holistic water quality analysis across the proposed systems. By comparing the treatment performance of both the bio-filters and VFCWs against established water quality standards for various reuse applications, the research provides a comprehensive understanding of integrated system performance. This inter-system analysis is critical for developing robust, scalable, and adaptable wastewater treatment and irrigation solutions.

5. Blueprint for Climate-Resilient Agricultural Systems: Ultimately, this research promotes a holistic and interconnected approach to sustainable agriculture. By meticulously investigating the interactions between water treatment (bio-filters, VFCWs), renewable energy utilisation (solar power), and efficient agricultural practices (drip irrigation), the findings will offer a replicable framework for enhancing water security, energy independence, and food production. This integrated Water-Energy-Food (WEF) nexus approach is vital for building climate resilience in agricultural systems globally.

LITERATURE REVIEW AND OTHER SPECIFIC WORK DIRECTLY RELATED TO THE 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 (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 recognised 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; Photo-degradation, which involves the breakdown of certain contaminants through light-induced chemical reactions; and Volatilization, where some contaminants transfer from water to air through evaporation.

RESEARCH REVIEW AND METHODOLOGY

Caribbean case studies have influenced the methodology for this wastewater quality management research, employing a mixed-methods approach with quantitative and qualitative techniques. Two experimental setups, Vertical Flow Constructed Wetland and Gravity Bio-Filter systems, were tested using two crops, Lettuce and Kale. The graphical representation of the research methodology is shown in the Flow Chart in Figure 1.

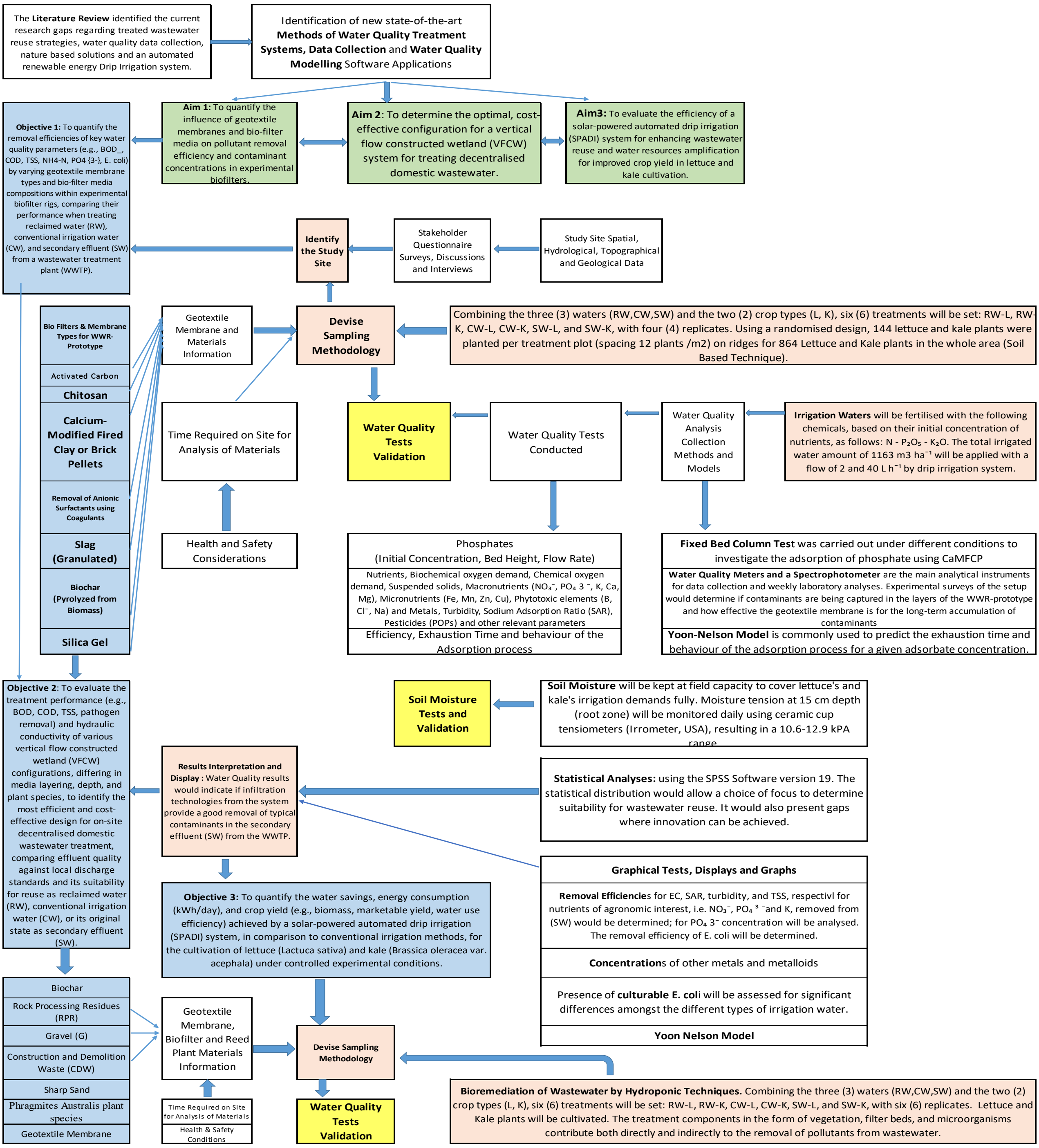

Figure 1: Flow Chart of Vertical Flow Constructed Wetland System for Wastewater Reclamation and Solar Power Drip Irrigation System (Source: Engineering Division, Ministry of Agriculture, Land and Fisheries, Trinidad.

RESEARCH METHOD

1. WWR-Prototype Design Experimental Setup for the Gravity Bio-filter System

The WWR-Prototype incorporates three storage tanks, with one tank for reclaimed wastewater, featuring layers of granular material and geotextile membranes, shown in Figure 2, engineered to gather treated wastewater (SW). The experimental setup facilitated all the flow and water quality measurements. Three 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 variations: (i) without a geotextile membrane, (ii) with an upper geotextile membrane, and (iii) with both upper and lower geotextile membranes. Weekly monitoring assessed water quality parameters, including nutrients, biochemical oxygen demand, and suspended solids, using meters and spectrophotometry to evaluate contaminant removal and membrane effectiveness. The system also includes advanced filtration with a biochar/chitosan/gravel profile for enhanced heavy metal ion sorption.

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 contaminant accumulation effectiveness of geotextile membranes and filters. 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 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 de-acetylation 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.

2. Wastewater Hydroponics/ Bioremediation System

A wastewater hydroponics system was implemented, whereby nutrients from the wastewater supports plant growth, requiring elements like nitrogen, phosphorus, potassium, iron, and zinc. The deep water hydroponic system employs physical, chemical, and biological methods for decentralized wastewater treatment and reuse. This system, which grows plants three feet above ground, is ideal for flood-prone areas and promotes treatment through microbial growth in a closed system with roots in flowing wastewater.

3. Crop Experimental Setup

The cultivation of lettuce (Lactuca sativa) is scheduled to occur over a 90-day period spanning from July to September 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 was selected for this study because of its 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 may offer protection against pathogens by shielding them from light exposure and desiccation, potentially facilitating their continued survival (Petterson et al., 2001).

4. 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 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 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 crop replicates. Using a randomised design, 144 lettuces and kale plants were planted per treatment plot (12 plants/m² spacing) on ridges, totalling 864 lettuces and kale plants in the entire area, shown in Figure 3.

5. Irrigation Water Analyses

Physicochemical analyses will be conducted for the 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 then rinsed and filled with water before collection. After transportation to the laboratory, the samples were stored at Five Degrees Celsius prior to processing.

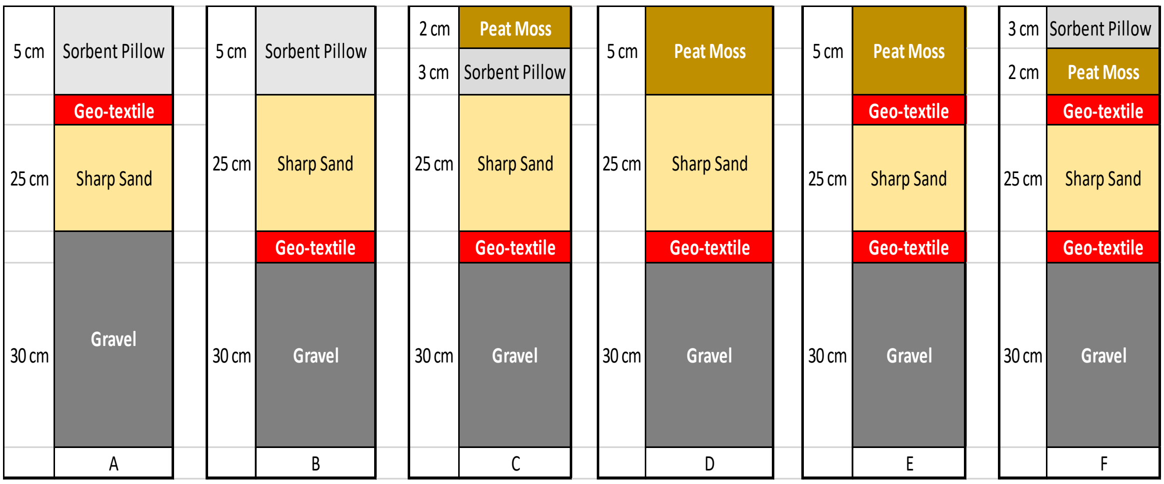

Figure 2: Illustration of the Layout of the WWR Prototype of Gravity Flow Bio-filter Systems

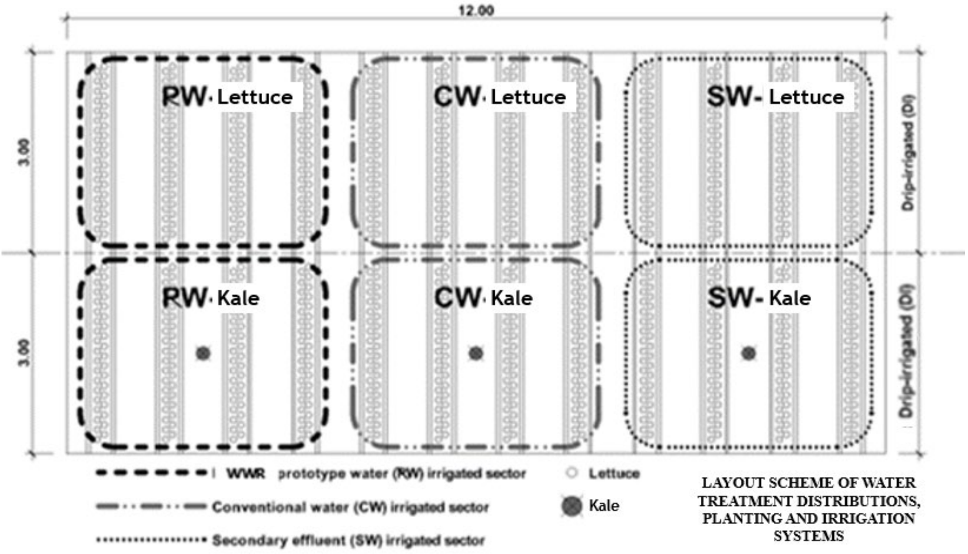

Figure 3: Layout Scheme of Water Treatment Distributions, Planting and Irrigation Systems

6. Vertical Flow Constructed Wetland System

A vertical flow-controlled wetland system designed for a single household should have a total surface area of 16 m² (Figure 4). The filter structure, with a total depth of 1.4 m, comprises of a 0.2 m drainage layer, a 1.0 m filter sand layer, and a 0.2 m insulation layer, shown in Figure 4. A 0.2 m high embankment surrounds the filter bed to prevent surface water intrusion. The filter bed is enclosed by a tight membrane (minimum thickness of 0.5 mm), protected on both sides by a geotextile. Common reed or Lilly (P. Australis) is planted in the bed at approximately four (4) plants/m² density, using either seedlings or rhizome pieces (Brix, 2003b).

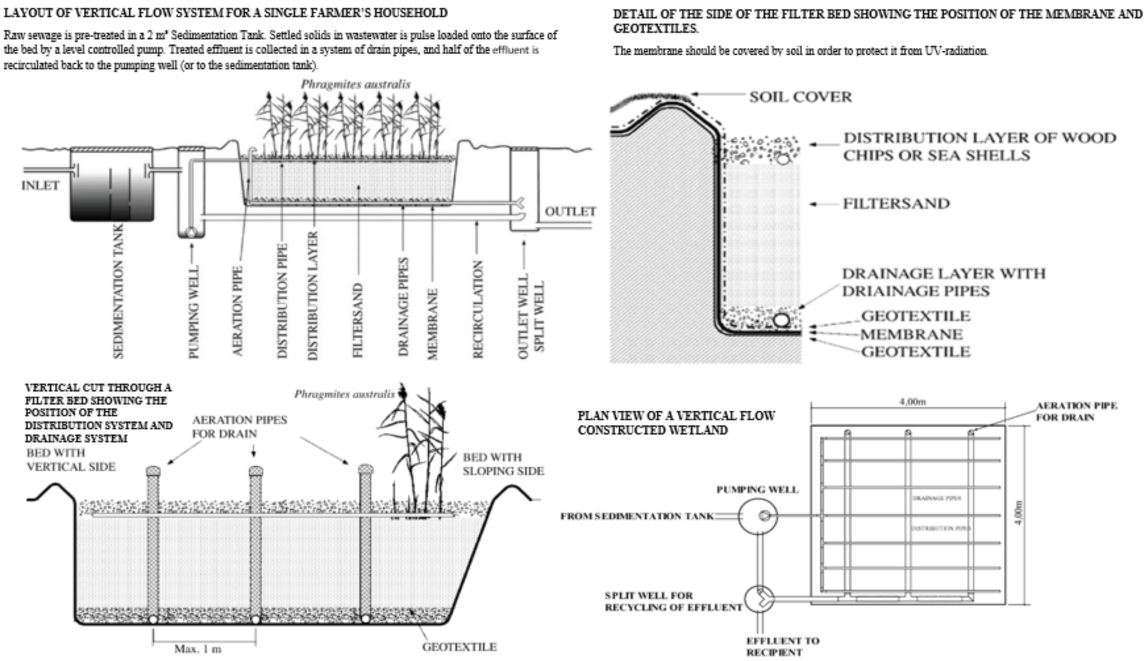

Figure 4: Layout of Vertical Flow Constructed Wetland System

7. Solar Powered Automated Drip Irrigation System

The installation of a solar-powered automated drip irrigation system utilising a pump and solar photovoltaic panels was employed to irrigate lettuce and kale crops, efficiently providing water directly to plant roots while reducing evaporation and runoff. This sustainable solution is vital for water-scarce regions like Trinidad. The system features a 3.0 kW solar panel array, designed to withstand winds up to 150 km/h, a 6 kW pure sine wave inverter, and a lithium-ion battery bank for reliable energy storage. Beyond water conservation, it reduces reliance on non-renewable energy sources. 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.

8. 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 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. 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:

$$\mathbf{n = n^{l} / [\ 1 + (n^{l} / N)]} \qquad (1$$

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).

RESEARCH 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 amongst 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 reaching the end user.

Crop Quality (Lettuce and Kale)

The water content of the lettuce and kale crops in the six 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 a drip irrigation 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 (OECD, 2002; UNECE, 2012).

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 hectare of agricultural land is 70 m^3/day/ha (with an Average Irrigation Water requirement of 7 mm/day), with variations depending on season, temperature and crop growth stage.

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.

DISCUSSION

1. Environmental Benefits:

The treated wastewater supply will promote environmental sustainability by connecting rural and urban areas, reducing pollutant discharge, and minimizing groundwater pollution while effectively utilizing 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 storm water 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.

2. Social/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.

3. 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 fertilizers, and lowering water treatment costs for downstream users.

4. 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:

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.
4. Development of Safe and Effective Wastewater Reuse and Irrigation Water Management
5. 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, pulverized 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 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 into the biological system, thereby protecting the micro-organisms 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, 2012). Water content in lettuces and kale amongst the six treatments should fall in the 93.0%- 94.9% range, thus not presenting significant differences. Total N concentrations are slightly over the optimum range (33-48 g/ kg) for the types of crop (Hartz et al., 2007). P concentrations are roughly within the optimum range (3.5-7.5 g /kg) (Hartz et al., 2007), but none of them reaches the detrimental threshold (10 g/ kg) (Marschner, 2012). K, Ca and Mg concentrations in drip irrigation treatments are slightly above their optimum ranges (29-78, 6-11, and 2.5-4.5 g/ kg, respectively) (Hartz et al., 2007).

Statistical Analysis

Analysis of the results is performed after conducting statistical analyses using 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. 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. Bunting et al. (2018) proved that spatial requirements for the facilities may be beyond the capacity of small islands. Prazeres et al. (2017) 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 anonymization 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 utilization of valuable plant nutrients while maintaining environmental compliance and mitigating risks in agricultural production. This study aims to stimulate the development of initiatives for nationwide adoption of wastewater reclamation schemes for agricultural irrigation and to enhance related policies and procedures.

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