Low cost urban wastewater infrastructure for environmental sustainability across Caribbean small island developing states (SIDS)

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ABSTRACT: Effluent Dominated Hydrosystems (EDHs) across the Caribbean primarily consist of surface water systems affected by discharged treated and possibly untreated runoff from urban and agricultural zones in addition to wastewater catchments. These urban water bodies are precious and vital natural resources beneficial to the Caribbean's economy, its environment and revitalisation. Human activities influence whether a hydrosystem consists of problems including excessive withdrawal for potable water supply, water quality, emerging contaminants from untreated stormwater runoff or wastewater. Land use patterns are one of the key driving forces behind changes in hydrology for EDHs. Runoff from agricultural land has also resulted in substances such as farm chemicals, petroleum products, nutrients and organic matter being washed into the surround EDHs. Historically, many industries across Trinidad and Tobago have been developed nearby natural hydrosystems with discharging pre-treated effluents directly into the water and transported away downstream. While such practices have been semi-regulated for several years by the Environmental Management Authority (EMA) for Trinidad and Tobago, several EDHs still consist of large amounts of pollutants present in sediments. This project evaluates the application of combined Biological and Photochemical (B-P) technologies as a low cost wastewater option for Small Island Developing States (SIDS) in the Caribbean. The application of B-P treatment for waste streams can significantly reduce industrial waste treatment cost, the water rates for farming and improve water quality in EDHs. The programme of research and implementation conducted by the University of Greenwich and the University of Trinidad and Tobago evaluates remediation technologies using two treatment processes (i) Biological and (ii) Photochemical. Although some organic contaminants can be degraded through biological process, many other composed synthetic compounds are non-biodegradable and hence the photochemical process will also be examined. The biological process is utilised like a pre-treatment step to enhance the photo-degradability and eliminate the toxicity of the effluents, whereby the total mineralization of contaminants would be completed in the photochemical process. The biological reactors are characterised by anaerobic respiration using pollutant-reducing bacteria as a terminal electron acceptor. These bacteria can thrive in human-impacted environments impacted by sewage or urban drainage. The photoreactor implements heterogeneous photocatalysts (readily available, cheap, non-toxic and inert semiconductors) such as Titanium Dioxide (TiO_2). In this process TiO_2 absorbs solar energy and transfers photonic energy to mobile toxic constituents. Various sources wastewater are being processed through the B-P reactors studying the kinetics of degradation.

1. INTRODUCTION

River water and marine pollution have become serious developmental issues facing Caribbean Small Island Developing states (SIDS). Early evidence of river and marine pollution was mainly anecdotal, but within the last 15–20 years deterioration of water quality has made several beaches unsuitable for swimming and oil spills have temporarily affected tourism. Organic and nutrient pollution, particularly from poor sewage treatment is one of the most serious river and marine pollution problem facing Caribbean SIDS. Petroleum hydrocarbons and sewage pollution problems persist in all parts of Trinidad, West Indies, while solid waste (particularly domestic water wastes), industrial pollution and pesticides are also significant contributors across the twin island republic of Trinidad and Tobago. The sources of water in Trinidad and Tobago include surface water (rivers and dams) approximately 66% of the supply and ground water (24%).[1] A desalination plant commissioned in 2002 supplied mainly high purity water for the industrial sector and accounts for the remaining 10% of the current supply. Nevertheless an unreliable supply of water has resulted in the unavailability of groundwater or surface water in close vicinity, difficulties in maintaining transmission lines from remote sources, economic infeasibility of development for water distribution systems to remote communities.

Table 1. Water demand sectors for Trinidad and Tobago (WASA, 2014)[1]

Category	Million cubic metres	%
Domestic	120	36
Major industries	51	15.1
Minor industries	10	2.9
Irrigated agriculture	10	2.9
Unaccounted for water	145	43.1
Total	336	100

The water distribution system from the Water and Sewerage Authority (WASA)[1] is antiquated and consequently there are frequent breakages along the system. These numerous breakdowns accounts for a substantial loss of water (40% annually). Additionally, the agricultural sector annual complaints of insufficient water for growing crops during the dry season and suffering substantial losses due to flooding in the wet season is a never-ending cycle facing Trinidad and Tobago. Inadequate irrigation systems also pose a threat to the countries health and supply of crops by farmers seeking to supplement water for agricultures purposes by pumping untreated grey water sources. Further water pollution problems include non-monitored use of untreated animal manure by farmers having fields in close proximity to rivers, faecal coliform levels increase by discharging domestic septic tanks along the river banks and groundwater sources become at risk from the applications of nutrients on agricultural fields and from several landfill sites that have no lining and are constructed in gravel pits.

Across the Caribbean SIDS, high population densities, combined with population growth, urbanisation and increased development, particularly residential and tourist resort development, have led to the contamination of underlying aquifers and surface water, and deterioration of water quality. Environmental and health concerns regarding agricultural and petrochemical waste have been responsible for a continually increasing public awareness and anxiety in the Caribbean. A combination of Biological and Photochemical (B-P) processes can be very effective and innovative methodology with great promise for a cost-effective technique for water reuse and conservation. This water once treated can be used for farming, agriculture and alternative water recycling purposes. Solar energy will be the driving factor for the disinfection stage. Effluent Dominated Hydrosystems (EDHs) which encounter flows from stormwater systems and centralised wastewater treatment plants can also be remediated. Urban water bodies are precious and vital natural resources beneficial to Caribbean SIDS economies, their environment and revitalisation. The bioremediation phase will degrade organic waste under controlled conditions to an innocuous state to levels below concentration limits established by regulatory authorities (World Health Organisation, United States Environmental Protection Agency, European Union Wastewater Directive). This process will utilise naturally occurring bacteria, fungi and plants to degrade and detoxify water contaminants hazardous to human health and the environment. The secondary treatment stage is an advanced oxidation process via photolysis and heterogeneous photocatalysis reduction/oxidation (redox) reactions from solar energy and UV radiation in catalyzing the electron transfer processes. Heterogeneous Photocatalysis (HP) is a viable option because standard solid-liquid separation processes or fixed-bed systems can be used. Photosensitizers used in HP are usually cheap, nontoxic and inert semiconductors. In this process, the semiconductors are used to absorb the solar energy and UV radiation thereafter transferring photon energy to the mobile toxic constituents being remediated. Reaction kinetics are dependent on the mobile toxic constituent concentration as well as the rate of adsorption of the constituent, the available surface area of the semiconductor, and the rate of desorption of the reaction products. This technology will directly impact EDHs for surface water quality by properly treating stormwater runoff and wastewater catchments applicable for agricultural zones. The application of B-P (Biological-Photochemical) treatment for EDHs will reduce industries water treatment costs and improve water quality in streams and rivers adversely affected by water pollution.

2. BACKGROUND

This project evaluated the application of combined Biological and Photochemical (B-P) technologies as a low cost sanitation option for Small Island Developing States (SIDS) in the Caribbean. The application of B-P treatment for stormwater and wastewater can significantly reduce industrial waste treatment cost, the water rates for farming and improve water quality in EDHs. The project and research aspects can provide promising remediation technologies for water treatment based on the combined technical characteristics and environmental performance criteria. Given the potential for serious environmental damage and burdensome reclamation costs, it is practical to seek long-term, cost effective treatments for stormwater/wastewater pollution. The two treatment processes evaluated in this project include (i) Biological and (ii) Photochemical. The efficiency of the Biological-Photochemical (B-P) processes depends on many factors such as the concentration of contaminants, pH and the presence of inhibitory compounds in water. Although some organic contaminants can be degraded through biological process, many other composed synthetic compounds are non-biodegradable and hence the photochemical process will also be examined. The biological process would be utilized like a pre-treatment step to enhance the photo-degradability and eliminate the toxicity of the effluents, whereby the total mineralization of contaminants would be completed in the photochemical process (see Figure 1).

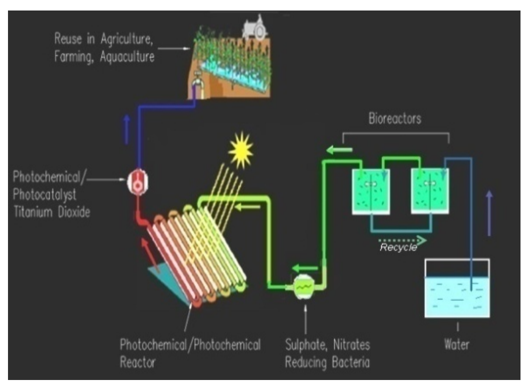

Fig. 1. Experimental set up for biological/photochemical treatment of stormwater and wastewater for reuse in the caribbean small island developing states.[2–5]

The group of beneficiaries for this research project includes farming villages and rural communities across the southern Caribbean islands (Trinidad, Tobago and Grenada). Outcomes from this project can lead to a comprehensive water action development plan for EDHs collaboratively with the relevant stakeholders (Local authorities, estate developers, businesses and the general public). The project will drive sustainable restoration of EDHs regarding water quality, biodiversity and habitats; including improved access and balanced usage of EDHs, promoting shared responsibility among the stakeholders of Caribbean SIDS water bodies. The information obtained from the research project can be included in reports and studies carried out by future researchers and will provide essential data and valuable knowledge in Water and Environmental Engineering applicable for the Environmental Management Authority for Trinidad and Tobago, the Water and Sewerage Authority for Trinidad and Tobago, and Grenada's National Water and Sewerage Authority.

3. LITERATURE REVIEW

3.1 *Photocatalytic treatment*

Homogeneous photocatalysis with aqueous photosensitizers and heterogeneous photocatalysis with solid photosensitizers are available options for mine water physiochemical treatment. Homogeneous photocatalysis, however, is rarely practiced due to the difficulty in separating aqueous species for recycling.[2–5] On the other hand, heterogeneous photocatalysis is more of a viable option because standard solid-liquid separation processes or fixed-bed systems can be used. The solid photosensitizers used in heterogeneous photocatalysis are usually cheap, nontoxic and inert semiconductors.

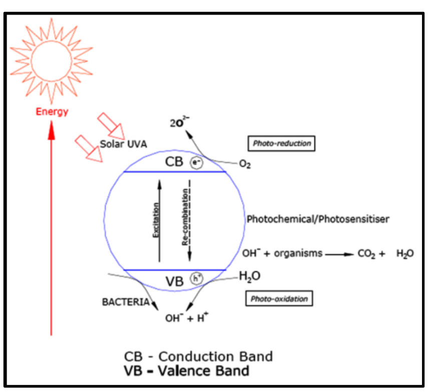

Fig. 2. Photochemical process of photosensitisers.[2–5]

In this process, solid semiconductors are used to absorb the solar energy and radiation and then transfer the photon energy to the mobile toxic constituent being remediated. However, electron transfer reactions can only occur if the mobile toxic constituent is adsorbed at the surface of the semiconductor. Thus, reaction kinetics are dependent on the mobile toxic constituent concentration as well as the rate of adsorption of the constituent, the available surface area of the semiconductor, and the rate of desorption of the reaction products. Reaction efficiencies are usually higher with heterogeneous photocatalysis due to the higher efficiency of photon capture and the increased "life" of the electron in the excited state.[2–5]

3.2 *Biological treatment via anaerobic digestion (AD)*

Biological pretreatment processes via anaerobic digestion biologically degrade organic waste streams under controlled conditions to an innocuous state or to levels below concentration limits established by regulatory authorities. The process uses naturally occurring bacteria to degrade and detoxify substances hazardous to human health and/or the environment. The microorganisms may be indigenous to the contaminated water or they may be isolated from elsewhere and brought to the reactor. Contaminant compounds are transformed by living organisms through reactions that take place as a part of their metabolic processes.[6–8] Biodegradation of a compound is often a result of the actions of multiple organisms.

For biological treatment processes via anaerobic degradation to be effective, microorganisms must enzymatically attack the pollutants and convert these into harmless products. Biological treatment of water and wastewater can be effective when environmental conditions permit microbial growth and activity. Its application often involves the manipulation of environmental parameters to allow microbial growth for degradation to proceed at faster rates. Biological treatment processes uses relatively low-cost, low-technology techniques which generally have a high public acceptance and can often be carried out close to the waste stream sites.[6–8] It's not always suitable, however, as the range of contaminants on which it can be effective is limited, the time scales involved are relatively long, and the residual contaminant levels achievable may not always be appropriate. Biological treatment via AD can be a good alternative to conventional technologies.

4. EXPERIMENTAL DETAILS

The experimental configuration of the water and wastewater treatment system included the pre-treatment stage of biological degradation (upflow anaerobic bioreactor) followed by photocatalytic oxidation processes. The pre-treatment stage enhances the removal efficiency process of the solar photochemical reactor. Flows through the reactors were continuous. The first phase of experimental testing for the water treatment pilot unit included contaminated river waters from North and Central Trinidad, West Indies.

The startup pilot scale experimental Upflow Anaerobic Sludge Bed Reactor (UASB) was carried out in a 10 Litre Pyrex container. The reactor included a central axis missing blade used every second for three to five minutes at a rotational speed of 100 rpm. Diluted fresh cow manure was used as the seed material for the starting-up phase of the UASB reactor. The feeding started 4 weeks after inoculation. The biological treatment stage consisted of a single tank process in an anaerobic reactor system with the principle objectives of achieving high removal of organic pollutants (Figures 3 and 4).

The photochemical reactor for the secondary treatment was a non-concentrating fixed bed tubular reactor. It does not concentrate radiation, so the efficiency is not reduced by factors associated with concentration and solar tracking. The reactor consisted of serpentine shaped tubing and was constructed with borosilicate glass (Pyrex glass), supported by an Aluminium metal frame as the reflector. These materials are available locally across the Caribbean and is sufficiently durable to weather the effects of sunlight and scratches.

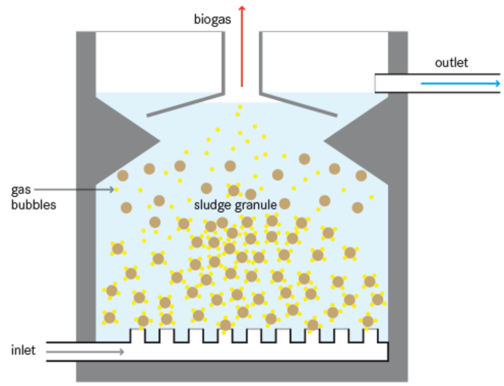

Fig. 3. Schematic of upflow anaerobic sludge blanket reactor (UASB) used for biological pre-treatment processes. Adapted after.[6–8]

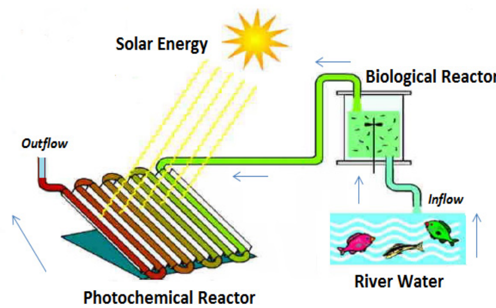

Fig. 4. Configuration of water flows from biological treatment to photochemical oxidation.[2–8]

Fig. 5. Solar photoreactor in operation, Trinidad, West Indies.

The materials chosen for both the bioreactor (Anaerobic digestion system) and the solar photoreactor were weather resistant and chemically insert to ultraviolet transmission. The angle of inclination for the solar reactor was set at 12° to approximate the latitude of Trinidad, West Indies (10.7°N) for optimum solar irradiation. This orientation of the solar reactor and its set inclination angle from the horizontal provide the necessary conditions for maximum influx of solar radiation.[2–5] Other angles of inclination could prove just as effective because of the rounded shape of the tubes. The dimensions of the glass tubing were as follows: total length, 12 m; outer diameter, 19 mm; wall thickness, 1 mm; capacity, 5 L. The solar reactor prevented air-gap formation by inducing an upward flow of floating bubbles. All the piping in this project was made of transparent polymer tubing or polyvinylidenefluoride (PVDF). This material was chosen because it is resistant to corrosion by contaminants and their possible by-products. PVDF tubing is inert to degradation by UV solar radiation and is a compatible material for the solar photochemical facility. This tubing is also strong enough to withstand varying pressure drops across the system. The Raw water tank constructed was a plastic insulated tank, insulated with fiber glass, 76 mm thick around the plastic tank. The fiber glass has a Thermal Conductivity value of k = 0.050 (W/mK). Aluminium sheeting was used around the entire tank as a radiation shield. These modifications were made to the raw water tank, so that the bacteria and the organic pollutants to be tested thorough the photochemical reactor were not affected by thermal changes or solar radiation in the intake reservoir. A water level gauge was set at a fixed height using transparent glass tubes so that when the level of raw water or water to be treated reaches 40 litres the tank will not be filled anymore.[2] The photocatalyst Titanium Dioxide (TiO_2) was selected for the second stage treatment process. Low dosages of TiO_2 were selected for the river water treatment processes ranging from 2.5–4.0 mg/l.

4.1 *Water quality analysis*

A range of measurement methods has been used in testing the river water and wastewater samples.[17–22] A pH and temperature reader (Aquaread, UK) was used to measure the influent and effluent stages of the bioreactor and the photoreactor. A Lovibond® BOD_5 (Biochemical Oxygen demand) sensor system BD 600 that allows precise measurement of BOD based on the manometric principle was used (Tintometer, 2016). Chemical Oxygen demand (COD) values were measured using Hach Lange LT 200 spectrophotometer and a Hach Lange Spectrometer DR 1900. Phosphates, ammonium, nitrates and nitrites were measured using indicator tubes and a Hach Lange LT 200 meter and Hach Lange Spectrometer DR 1900. Turbidity was measured using a Hanna Turbidity meter and a 10 ml cuvette. Color of the water samples tested was recorded using a Hanna color checker and two 10 ml cuvettes.

5. RESULTS AND DISCUSSION

The project effectively removed BOD and COD concentrations, significantly reducing the turbidity, colour, nitrites and ammonia present in the river water (see Figures 6 and 7). The effectiveness of biological degradation followed by photochemical oxidation processes have shown to be a viable solution by supplying oxidants and non-toxic photoabsorbers which were capable of absorbing photons from sunlight and increasing the rates of photocatalytic oxidation. The photocatalytic process was an economical and readily available system practical for Caribbean countries. The decomposition during the biological phase of inorganic and organic contaminants occurred as a result of the electrochemistry of the system, pH, temperature conditions and concentrations of ions. The upflow anaerobic reactor performed well reducing BOD, COD and organics loadings by 50–70% respectively. This performance has been similar to previous studies whereby anaerobic digestion was the principal treatment process.[11–17] Photocatalytic degradation during the second stage treatment is a result of a well-defined (oxidation-reduction potential, pH, concentrations of ions and ambient temperatures).[2–4] If the proper solar intensity and frequency of electromagnetic radiation is available, greater removal efficiencies are usually associated with the process. This radiation (natural sunlight) can occur

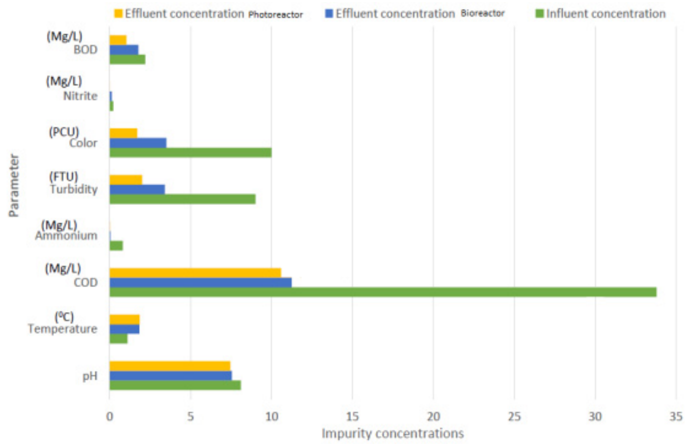

Fig. 6. Average treatment performance of river water from north Trinidad. Sample no. = 173, from February 2014–March 2015.

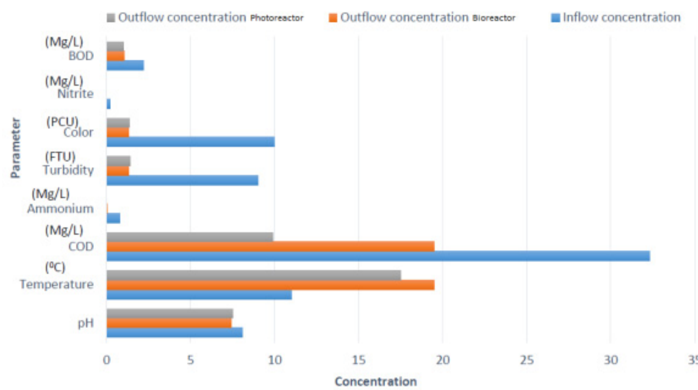

Fig. 7. Average treatment performance of river water from central Trinidad. Sample no. = 173, from February 2014–March 2015.

during sunny spells, but inevitably may require artificial energy sources to accommodate seasonal, daily, and hourly changes due to winter, nightfall, and cloudiness. Continuous studies include ultraviolet oxidation using high-pressure mercury lamps versus solar energy efficacies.[5]

Photoreduction occurs in the reactor when the absorbing compound donates the excited electron to another species. The photooxidation process occurs when the absorbing compound accepts an electron from another species in order to fill its electron vacancy. The excited electron will eventually relax to the ground state of the reaction products.[2–5] Energy needed to promote electrons from the ground state to the excited state is usually equivalent to that possessed by Ultraviolet (UV) radiation. Photolytic reactions also occurs which are induced directly from the absorbing compound is the species being remediated or indirectly if the absorbing compound is available for transferring the photon-energy to the species being remediated. The photolysis process can also occur in the absence of the photocatalyst or in their presences as an aqueous species (homogeneous photolysis and photocatalysis) or solid semi-conductors (heterogeneous photocatalysis).

Other semiconductor photocatalysts will also be evaluated and tested such as ZnO, $FeTiO_3$, SiO_2, Fe_2O_3, ZnS and CdS, and its relation to the photo-degradability of water pollutants. The titanium dioxide as a metal oxide works best because of its chemical stability and high quantum efficiency for photoconversion and photo-degradation.

6. PERSPECTIVES

The need for alternative water resources, coupled with increasingly stringent water quality discharge requirements, are the driving forces for developing water reuse strategies in the developing world today. Water reuse enables practitioners to manipulate the water cycle, thereby creating needed alternative water resources and reducing effluent discharge to the environment.[9] The growing trend is to consider water reuse as an essential component of integrated water resources management and sustainable development, not only in dry and water deficient areas, but in water abundant regions as well. In areas with high precipitation where water supply may be costly due to extensive transportation and/or pumping, water reuse has become an important economic alternative to developing new sources of water.[9]

The main drivers for water reuse development for Small Island Developing States are:

- Increasing water demands to sustain industrial and population growth. This is the most common and important driver for dry and water-abundant regions in developed, developing, and transitional countries.
- Water scarcity and droughts particularly in arid and semi-arid regions. In this case, reclaimed water is a vital and drought-proof water source to ensure economic and agricultural activities.
- Environmental protection and enhancement in combination with wastewater management needs represent an emerging driver, in a number of industrialized countries, coastal areas, and tourist regions.
- Socio-economic factors such as new regulations, health concerns, public policies, and economic incentives are becoming increasingly important to the implementation of water reuse projects.

A prerequisite of sustainable development is to ensure the protection of streams, rivers, lakes and oceans from contamination. Environmental and health concerns regarding waste management have been responsible for continually increasing public awareness and anxiety across the Caribbean region. There are increased concerns regarding the toxicity and contaminant potential of wastes and these must be a re-evaluation of the potential risks and acceptability of wastewater treatment and reuse in many areas.

7. CONCLUSION

Water management across the Caribbean region should be driven by the need for secure access to sufficient quantities and safe quality of this precious natural resource. Fundamentally, good water management plans are required to ensure that production levels are not threatened by the lack of water resources of environmentally altering water supplies. Increasingly the public and health authorities are becoming aware that there is a need to protect and conserve water resources and not only engineer against large catastrophic releases of waste into natural hydrosystems, but also against probable and futuristic slow releases of waste streams which occur over a period in time. Hence, it is the engineer's responsibility to minimise pollution and design novel and sustainable water and wastewater treatment process in dealing with surface water and groundwater pollution over a longer period in time. The environmental future of Caribbean SIDS countries depends on their abilities to deal effectively with waste problems of the past, present and most importantly to prevent and mitigate waste problems in the future.

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