Developing a Pilot Scale Horizontal Sub Surface Flow Constructed Wetlands for Phytoremediation of Primary Lagoon Effluents

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Abstract

Wastewater discharge is a threat to nature, causing eutrophication and water borne diseases. The situation is getting worse with rapid urbanization where adequate sanitation and wastewater treatment facilities are lacking. Constructed wetlands (cw) are designed to mimic natural wetlands with much degree of control. Despite recognizing cw as an alternative for conventional wastewater treatment, little has been done in developing countries. This study aims at developing a pilot scale horizontal subsurface flow cw for treatment of primary lagoon effluent. Experimental set - up would consist of three vegetated cells and one non-vegetated cell control. Cells would be packed with 5-10mm diameter pea gravel while 20-50mm diameter pea gravel will be used at the inlet and outlet areas to prevent clogging. Hydraulic residence time (HRT), shall be established from previously published research. Sampling shall be done twice a month for a period of 2 years. SPSS software shall be used for statistical analysis.

Keywords

Constructed wetlands; Wastewater effluents; Treatment; Developing countries.

INTRODUCTION

Exploitation of natural resources to ensure comfort and well being under an illusion that the demand for the natural resources could never exceed supply has led to depletion of natural resources with little regard for conservation and its sustainability. The generation of liquids and solids wastes as a result of human settlement and industrial activities pollute most of the watercourses (Abdel-Halim et al., 2008). It is noted that the quantity of wastewater will increase along with population growth. The increasing scarcity of water in the world along with rapid urbanization calls for concern and the need for appropriate water management practices.

Untreated or partially treated wastewater release is harmful to the environment; hence, restrictions should be imposed on wastewater discharge to protect the environment (Katayon et al., 2008). Very little investment has been made in the past on sewage treatment facilities. Water supply and treatment often received more attention and priority than wastewater collection and treatment (Abdel-Halim et al., 2008). However, due to trends in urban development wastewater deserves greater emphasis. Currently, there is a growing awareness of the impact of sewage contamination on rivers and lakes. The United Nations Environmental Programme (UNEP), World Health Organization (WHO) and Global Environmental Monitoring Systems found organic material from Agro-industrial effluent municipal waste and domestic sewage to be the most common water pollutant (Adelegan, 2007). It was observed that about two-thirds of the populations in developing countries have no hygienic means of disposing excreta and even greater number lack adequate means of disposing total wastewater. Inadequate sanitation is one of the prime causes of disease. Also, the provision of sanitation is not keeping up with population growth (Abdel-Halim et al., 2008).

Constructed wetlands are artificial wastewater treatment systems consisting of shallow (usually less than 1m deep) ponds or channels which have been planted with aquatic plants. The systems rely upon aerobic bacteria, biological, physical and chemical processes to treat wastewater (Akratos and Tsihrintzis, 2007). These constructed wetlands have impervious clay or synthetic liners, and engineered structures to control flow direction, liquid detention time and water level. Depending on the type of system, they may or may not contain an inert porous media such as rock, gravel, or sand. The subsurface flow (SSF) consists of a basin or channel with a barrier to prevent seepage, but the bed contains a suitable depth of porous media. Rock and gravel are the most commonly used media. The media also support the root structure of the emergent vegetation (Vymazal, 2010).

The uses of constructed wetlands are alternative to conventional activated sludge wastewater treatment methods which are often used to improve facultative lagoon effluents. The benefits include, low cost associated with maintenance, operation and energy requirements and overall decrease of risk posed to the environment and public health by discharge of contaminated wastewater (Katsenovich et al., 2009). Constructed wetlands treatment facilities confers significant benefits to agricultural efforts, in particular to the growth of non-food crops, because many essential nutrients and minerals found in wastewater considerably reduce the need for expensive chemical fertilizers. The performance of constructed wetland facilities under tropical conditions has not been extensively researched in previous studies (Katsenovich et al., 2009). In spite of the assumption that the performance of constructed wetland processes are more efficient in equatorial regions than those in temperate regions, plant growth and microbiological activity throughout the year round are encouraged by warmer weather with positive effect on treatment parameters (Bojcevska and Tonderski, 2007).

Constructed wetlands are complex systems with large number of active physical, chemical, and biological processes that mutually influence each other. Therefore constructed wetlands have been often considered as “black boxes” and only little effort has been made to understand the main processes leading to wastewater purification (Brix and Johansen, 1999). The design of constructed wetlands has been carried out with different models, among which are; rules of thumb and regression equation, the well known first-order K-C* model, monod-type equations and a complex dynamic compartmental model. The constraints and parameter uncertainty of each model was reported by Rousseau et al., (2004). However, many parameters are difficult to measure and therefore many assumptions must be made. Hence it is important, to realize that more complex models do not necessarily bring more precise design parameters. However, no matter which design model is used for municipal sewage, the area of horizontal flow constructed wetlands is usually about $5m^2$ PE^{-1} (Vymazal and Kropfelova, 2008). To achieve the outflow BOD_5 and TSS concentration of 30mg/l, the U.S. EPA recommends the respective in flow loads of $6g/m^2$ d and $20g/m^2$ d (Vymazal, 2010).

Horizontal subsurface flow constructed wetlands have been designed using either simple “rule of thumb” set at $5m^2$ PE^{-1} or plug-flow first order models (Kadlec et al., 2008). Recently, more complex dynamic, compartmental models (Langergraber et al; 2009) have been developed. Sizing of horizontal subsurface flow constructed wetlands is usually based either on volume or area. Volume–based methods use a hydraulic retention time to assess the pollutant removal while area-based method wetlands assess pollutant reduction using the overall or total wetlands area necessary to remove BOD_5, TSS, Phosphorus, Nitrogen, Organic nutrients and pathogens (Katsenovich et al., 2009).

Problem Statement: Conventional high-technology wastewater treatment system are in many situations not a suitable solution in developing countries because it is not sustainable to install wastewater treatment facilities which require guaranteed power supply, replaceable spare parts and a skilled labour for operation and maintenance (Konnerup et al., 2009). Another issue is treatment requirement. In developed countries, the goal is elimination of all pollutants like pathogens, nutrients, organic and inorganic chemicals. Whereas, the primary treatments aim in developing countries is protection of the public health through control of pathogens to prevent transmission of water borne diseases (Kivaisi, 2001). For this purpose constructed wastewater systems are suitable since they can be efficient in removal of BOD_5, pathogens and nutrients (Konnerup et al., 2009). Despite the recognition of constructed wetlands technology as an excellent alternative for conventional wastewater treatment systems, not much work has been done to determine its applicability in humid tropical environment.

Hence, this study aims at developing a pilot scale horizontal subsurface flow constructed wetlands system for treatment of primary lagoon effluent (sewage) located opposite Obafemi Awolowo Hall, University of Ibadan (Figure 1). The project also evaluates the effectiveness of three aquatic tropical plants (*Canna Indica, R. Phragmites australis* and *Sacciolepis africana*), varied hydraulic retention time and hydraulic loading rate on the strength of the final effluent. The specific objectives were to design, construct and conduct operational testing of horizontal subsurface flow treatment wetlands over a period of two years with the use of three different aquatic tropical plants in treatment of primary lagoon effluents. Also, the study sets to investigate the effects of varying hydraulic retention time (HRT) and varying Hydraulic loading rate (HLR) in mass removal rate of $BOD_{5,}$ COD, TSS, TN, NH_4 - N, TP, and FC in gravel based subsurface flow treatment wetlands. Furthermore, seasonal effects on the treatment efficiencies of the constructed subsurface flow treatment wetlands will be analyzed.

Experimental site will be located within the University of Ibadan, Nigeria. Ibadan is in the south western part of Nigeria with a tropical climate of variable rainy and dry seasons. The city is situated in the forest zone close to the boundary between the forest and the savannah. Ibadan lies roughly between latitude 07^{0} 29’ 16N and longitude 03^{0} 54’ 44E, at an altitude of about 213.4m above mean sea level (Eze, 1997). It has a humid equatorial climate with warm temperatures, high humidity and rainfall with peak dry and wet seasons around February to April and June to August respectively. Annual rainfall for Ibadan is between 1000-1600mm, with the mean around 1270mm (Lal, 1993). Approximately, 50% of the average annual rainfall occurs between April and July while 40% occur between August and October. November to March is usually the driest months and temperature tends to be higher.

Figure 1: Anaerobic Lagoon for Sewage Treatment.

METHODOLOGY

Experimental set up would consist of three vegetated cells and one non-vegetated cell to serve as a control experiment. The cells would be replicated; each bed will be X meters long, Y meters wide and Z meters deep. The exact size of matrix of the subsurface wetlands to be constructed depends on the influent Biological oxygen demand (BOD_5), Total suspended solids (TSS) and Nitrate ($N0_3^-$) concentrations of the wastewater according to Metcalf and Eddy (2004), Katayon et al., (2008). The treatment area would be packed with 5-10mm diameter pea gravel while bigger and larger gravel of 20-50mm diameter will be used at the inlet and outlet areas in order to prevent clogging of the filter media. The cells will be coated with anti-rust paint and lined with water resistant material such as a low-density polyethylene sheet. The constructed wetlands cells would have bottom slope of 0.5-1.0% to facilitate hydraulic head measurement.

Surge tank of 1000 litres capacity will receive wastewater while two settling tanks of 500 litres capacities each would be connected to surge tank. A 2Hp pump will be connected to the settling tank which would pump wastewater to an over head storage tank of 1000 litres capacity. The arrangement of the inlet and outlet pipes and distribution of wastewater within the cell would be similar to previous studies (Ghosh and Gopal, 2010; Konnerup et al, 2009). The young sprouts of the three plants to be used would be planted equidistantly at 20cm interval in all the treatment cells. The plants shall be allowed to grow and multiply until dense stand are formed in the cells over four month period. There will be a periodic application of wastewater to serve as a source of nutrients for the plants, before selected inflow rates of wastewaters is introduced.

Operational procedure: The primary lagoon effluents would be piped into the cells and flows through. The elimination processes takes place during this passage. They are based on various complex physical, chemical and biological processes within the association of substrate, macrophytes and microorganisms: settling of suspended particulate matter, filtration and chemical precipitation through contact of the water with the substrate, chemical transformation, adsorption and ion exchange on the surface of plants, substrate, sediment and litter breakdown, transformation and uptake of pollutants and nutrients by microorganisms and plants, and natural die – off of pathogens. To evaluate the effect of HRTs on treatment efficiency, each of the cells will be operated with different HRT. The flow pumped to each treatment cell would be calculated by taking into account the stated theoretical HRT, porosity and area.

Sampling: Sampling shall be done twice a month for duration of 2-years. Samples shall be transported immediately from point of collection to laboratory for analysis. Samples shall be measured for pH, Temperature, total Suspended Solids (TSS), Biological oxygen demand (BOD_5), Chemical Oxygen Demand (COD), Total Phosphorus (TP), Total Amnonia Nitrogen (NH_4^+), Nitrate (NO_3^-) and Total coliforms; following the procedure of APHA (1999).

Data Analysis: SPSS software shall be used for the analysis, using one way Analysis of Variance (ANOVA) and post hoc test after ANOVA.

Preliminary Results

The Design: Constructed treatment wetlands modeling consists of first–order equations which in case of constant conditions (e.g. influent, flow and concentrations) and an ideal plug-flow behavior predict an exponential profile between inlet and outlet (Rousseau, et al., 2004). Because of complex web of interactions in a constructed treatment wetland leading to parameter uncertainty and some unexplainable assumptions in design, this study applied the “rule of thumb”. Though it is a conservative design model, easily applicable and can guarantee good quality effluents, it tends to increase the investment costs.

The preliminary study on the primary lagoon effluents by Ewemoje and Sangodoyin (2009), showed the following physico-chemical and microbiological parameters (Table 1) of treated sewage wastewater. The preliminary results which will serve as the influent into the constructed wetland are used in the horizontal subsurface flow wetland systems design.

Table1: Characteristics of the Primary Lagoon Effluents

Parameter	**Effluent Ranges**	**FEPA Limit**
COD	420 – 450	80
BOD_5	245 – 287	30
Total Solid	3050 – 3165	-
Total Dissolve Solid	1050 – 1160	2000
Suspended Solid	1997 – 2005	20
Turbidity ((NTU)	95 – 193	-
Total Coliform Count (cfu/100ml)	2.2 - 3.3	500
Ammonia	200 – 215	-
Nitrate	103.5 – 110	20

All parameters in mg/l except where stated

Having considered all the different models for design of constructed wetlands, this study base its design on the following equation first proposed by Kickuth, and is widely used for sizing of horizontal subsurface flow wetlands systems for domestic sewage treatment. (Vymazal, 2008)

$$A_h = Q_d\,(InC_{in} - InC_{out})/K_{BOD} \qquad \ldots \qquad \text{(i)}$$

Where; A_h is surface flow of bed (m^2); Q_d is average flow ($m^3\ d^{-1}$); C_{in} is influent BOD_5 (mg l^{-1}); C_{out} is effluent BOD_5 (mg L^{-1}); and K_{BOD} is the rate constant (md^{-1}).

The K_{BOD} value is usually lower, ranges between (0.07- 0.1m d^{-1}) but according to Vymazal (2008) many countries used values around 0.08m d^{-1}.

Size Calculations: To determine the Population Equivalent(P.E.) for each cell based on typical unit organic loading 45g /P.E./day and this varies from 0.13 -0.44 P.E. depending on Hydraulic Retention Time (HRT). From equation (i);

A_h is unknown

Q_d = 0.18g/P.E./day

C_{in} = 287 mg/l

C_{out} = 30 mg/l

K_{BOD} = 0.08md^{-1}

$$A_h = 0.18(In287 - In30)/0.08$$

Therefore, A_h = 5.08m^2 PE^{-1}

However this sizing is suitable for BOD_5 and suspended solids removal but not appropriate for removal of nitrogen and phosphorus. The aspect ratio (Length: width) also changed over the years, while the early system used to have long and narrow trenches with aspect ratio (length: width) > 1. Based on this, a length to width ratio of 3:1 will be used in the design. Therefore the surface area of each cell given by Fowler (2003) is:

Area = $3W^2$

Substituting values gave 5.08 = $3W^2$

Therefore W = $(5.08/3)^{0.5}$ = 1.30m

Hence, L = 3 x 1.30 = 3.9m

However, the width currently being used according to Vymazal (2008), is less than 1. Hence a W value of 0.75m is chosen, for ease of construction, considering that each cell will have a surface area of $2.25m^2$ for effective BOD_5 removal (Katsenovich, et al., 2009). Therefore to have a length to width ratio of 3:1, the actual length of constructed wetland will be 3.0m to minimize cost of construction and maintenance of the wetlands without undermining its treatment efficiency.

Thus actual area of wetland designed is $2.25m^2$ (i.e. 0.75 x $3.0m^2$)

CONCLUSIONS

This is an ongoing first year PhD research work and design considerations with wetlands treatment bed size matrix which is one of the set out objectives has been achieved. However, at the end of this research work it is expected that the designed and constructed treatment wetland would be used in treating primary lagoon effluent with three different aquatic tropical plants. Also, the effects of varying hydraulic retention time (HRT) and varying Hydraulic Loading Rate (HLR) would be investigated. Furthermore, mass removal rates of BOD_5, COD, TSS, TN, $NH_{4,}$ NO_3, TP and FC in gravel based subsurface flow treatment wetlands effluents would have been studied while seasonal effects on treatment efficiencies of the constructed subsurface flow treatment wetlands effluents in tropical environment over a period of two years would be determined.

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