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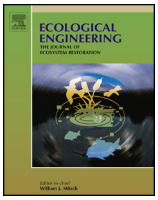

Municipal wastewater treatment using sequential activated sludge reactor and vegetated submerged bed constructed wetland planted with *Vetiveria zizanioides*

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ABSTRACT

This study investigated a sequential system consisting of Biological Nutrient Removal Activated Sludge (BNRAS) and Vegetated Submerged Bed Constructed Wetlands (VSBCW). The BNRAS/VSBCW combination removing pollutants from municipal wastewater in a developing country was examined. Wastewater from the anaerobic, anoxic and aerobic zones of the BNRAS was fed into 12 pilot VSBCW consisting of 1000 L plastic tanks having 500 mm deep 10–15 mm diameter granite substrate planted with *Vetiveria Zizanioides*. Irrigation of macrophytes using effluent from the BNRAS was done after 3 months of planting and the VSBCW effluent analyzed. Wastewater samples were collected and analyzed using standard procedures. Percentage removal of 96.6, 96.93, and 97.21% of COD; 33.33, 85.71, and 92.48% of Nitrate/Nitrite; 53.51, 46.45, and 88.78% of Sulphate; and 98.34, 99.72, and 99.6% of TSS were obtained from the anaerobic, anoxic and aerobic zones respectively. Removal efficiency from the anaerobic zone effluent was highest during the study period. VSBCW using locally available macrophytes *V. Zizanioides* in combination with BNRAS was found efficient in municipal wastewater treatment.

1. Introduction

The Biological Nutrient Removal Activated Sludge (BNRAS) process comprising of biological reactor and a secondary settler is used widely as secondary treatment for both municipal and industrial wastewaters. There are problems associated with BNRAS which makes it difficult to recycle its effluents directly. According to Martins et al. (2004); Graham and Smith (2004), unsuccessful sludge settlement and failure of wastewater treatment due to loss or inactivation of key populations are some of the problems associated with BNRAS effluents. Wastewater treatment using conventional BNRAS requires long sludge age for nitrification and there is always difficulty in near complete nitrogen removal (Muller et al., 2004). To achieve higher effluent quality, membrane systems such as microfiltration, ultra filtration and reverse osmosis are used (Bai and Leow, 2002). This treatment processes are expensive and requires high level of skill workers. External Nitrification is employed in some cases as observed in Muller et al. (2004). However, there is need for low cost alternative tertiary wastewater treatment systems which Constructed Wetlands provide.

Constructed Wetland (CW) is a cost-effective wastewater treatment alternative with promising performance to treat domestic, agricultural and industrial wastewater (Badejo et al., 2015: Kouawa et al., 2015). CWs act as bio-filters to remove nutrients, pathogenic microorganisms, persistent organic pollutants and trace elements from industrial and domestic wastewater (Kadlec and Wallace, 2009; Brix, 1997). They are engineered ecosystems that use natural processes involving wetland vegetation, soils and microbial assemblages in improving the quality of water usually in a controlled environment (Maine et al., 2007; Vymazal, 2011).

CWs are complex matrix of distinct aerobic and anaerobic treatment zones. They are wastewater treatment facilities duplicating the processes occurring in natural wetlands. Constructed wetlands can be classified based on the type of macrophytic growth (emergent, submerged, free floating and rooted with floating leaves) or the water flow regime (surface flow, sub-surface, vertical or horizontal flow). They are classified broadly as Free water surface (FWS) wetlands or surface flow (SF) constructed wetlands, and

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Vegetated submerged bed (VSB) systems or subsurface- flow (SSF) constructed wetlands (USEPA, 2004; Arias and Brown, 2009).

CWs technology has been reported to offer lower construction and maintenance cost for domestic wastewater treatment and is suitable for developing countries (Ayaz and Akca, 2000; Badejo et al., 2012). For a long time researchers have pointed out the high pollution removal capacity of natural environment (soils, wetlands, etc) and studies have been ongoing on the possibility of using natural environment in order to purify or complete wastewater purification (Chen et al., 2008; Chung et al., 2008). CWs have been used to remove a wide variety of pollutants ranging from organic compounds, suspended solids, pathogens, metals and nutrients (Kadlec and Wallace, 2009).

Natural processes involving wetland vegetation, soils and their associated microbial assemblages are employed in CWs to improve water quality. Kadlec and Wallace (2009) described the wetland processes that contributes to the removal/reduction of pollutant in CW as microbial mediated processes (removal as a result of the activity of bacteria or other microorganisms); chemical networks (creating products that are themselves contaminants of interest); sorption (either linear, fruendlich or Langmuir); volatilization (resulting in the creation of gases that are released to the atmosphere); sedimentation (mostly involving suspended solids); photodegradation (whose effectiveness is determined by the concentration of organisms and the radiation dose rate); plant uptakes (in which plants take up nutrients and trace chemicals to sustain their metabolism and for storage respectively); transpiration flux; vertical diffusion in soils and sediments; seasonal cycle, and accretions (creation of new soils and sediments).

Li et al. (2015) summarised the process of pollution removal in subsurface wetlands as involving multi-functioning substrate, microorganisms, and macrophytes as the wastewater flows through the Wetland Bed. Vegetation plays an important role in CWs, especially on nitrogen and phosphorus removal (Bachand and Horne, 2000). Macrophytes perform notable metabolic and absorption functions, their transport system take up nutrients and contaminants from the substrates or water. Vegetation have been shown to have a significant positive effect on wastewater pollution removal (Brisson and Chazarenc, 2009; Akratos and Tsihrintzis, 2007). Macrophytes provide a large surface area for attached microbial growth and supply reduced carbon and oxygen, the macrophytes used in CWs are usually tolerant to high organic and nutrient loadings from the wastewater; they have rich root and rhizomes that would provide substrates for the attached bacteria (Vymazal and Kropfelova, 2005). The use of vetiver in the treatment of wastewater started in Australia in 1996 where the secondary treated effluent was used for lawn irrigation (Truong, 2000). Research also showed vetiver's tolerance to elevated and sometimes toxic levels of salinity, acidity, and alkalinity as well as a whole range of heavy metals and agrochemicals (Truong, 2000; Wagner et al., 2004). *Vetiveria Zizanioides* is locally available in South Africa at commercial rate and easily accessible.

A valuable source of water in a semi-arid country such as South Africa is the reuse of wastewater. The city of Tshwane, Gauteng province, South Africa has ten wastewater treatment plants (Babelegi, Temba, Rietgat, Klipgat, Sandspruit, Rooiwal, Zeekoegat, Baviaanspoort, Sunderland Ridge and Daspoort). In the Daspoort Wastewater Treatment Works (DWWTW) a certain degree of indirect reuse of treated effluent is currently taking place. The treated wastewater effluent is discharged into Apies River and it flows into dams or reservoirs, from where it is withdrawn to water treatment plants. The quality of the treated effluent deteriorates in the dams due to some algal growth.

Wastewater treatment systems that employ a combination of conventional and less resource intensive ecologically sustainable system is therefore required in resolving the water supply and sanitation issues in developing country like South Africa. This research therefore, investigated the possibility of integrating a VSBCW using *Vetiveria Zizanioides* into a BNRAS for municipal wastewater treatment. The specific objective of the study was to determine the most appropriate placement of VSBCW when integrated into BNRAS in treating municipal wastewater in Guateng Province, South Africa. Effluents from the three different compartments of the BNRAS were subjected to treatment in a VSBCW planted with *Vetiveria Zizanioides*.

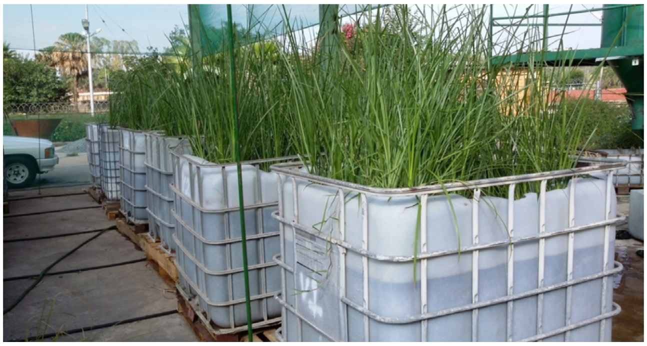

Fig. 1. Experimental setup showing a section of the pilot VSBCW with *V. Zizanioides*.

2. Materials methods

2.1. Study area

The study area of this research work is the Daspoort Waste Water Treatment Works, Pretoria, South Africa. It was built between 1913 and 1920 to the design of Town Engineer F. Waltone Jameson. The DWWTW and Rooiwal Waste Water Treatment Works treat wastewater collected from Central Pretoria. The DWWTW abstract raw water from the main sewer at two points linked to its Eastern and Western Works. The influent wastewater undergoes mechanical screening, grit removal and primary settling at the abstraction points. The Eastern and Western works consist of trickling filter plant (modules 1–6) and BNRAS system (Modules 9–11) respectively. The BNRAS has three modules with 9 compartments of 750 m^3 each. The modules are operated in a 3 stage configuration, anaerobic (1500 m^3) anoxic (2250 m^3) and aerobic (3000 m^3). The aerobic compartments are fitted with surface aerators and nitrogen rich mixed luquor are taken from it to the anoxic compartment. Effluent from the primary sedimentation tank and return activated sludge from the secondary sedimentation tank enter the anaerobic compartment (Muller et al., 2004).

Wastewater from the 3 different compartments of the BNRAS was pumped batch-wise into a green house consisting of 12 pilot Vegetated Submerged Bed Constructed Wetlands (VSBCW) built at the DWWTW, Pretoria, South Africa. The pilot VSBCW bed consisted of 1000 L plastic tanks (Fig. 1) with a surface area of 1.2 m^2 each. The substrate was 500 mm deep 10–15 mm diameter granite with 100 mm thick overlay of manure from the DWWTW sludge, to ensure adequate growth of the macrophytes before wastewater irrigation. Each bed was equipped with inlet and outlet pipes to ensure regular irrigation and effluent collection. The twelve VSBCW pilot beds were planted with transplanted rhizomes of *Vetiveria Zizanioides* from Hydromulch (PTY), South Africa.The macrophyte (*V. Zizanioides)* was planted at a distance of 200 mm apart to produce a high density bed. Irrigation was initially with tap water and irrigation with wastewater began three months after planting.

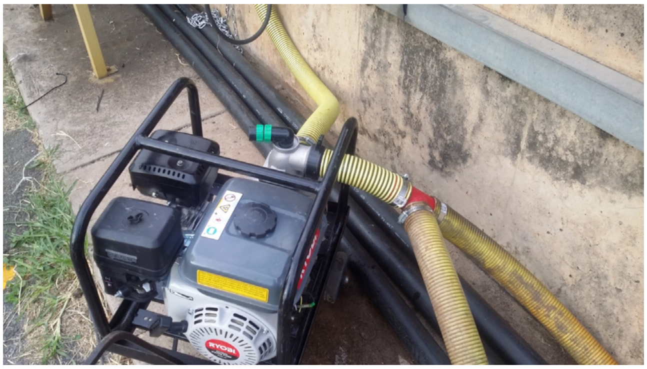

Fig. 2. RYOBI pump showing the connections used in irrigation.

Table 1
Characterisation of wastewater during study period.

Parameters	Range		Mean	Standard Deviation
Alkalinity, Total (mg/L $CaCO_3$)	232	320	297	27.31
COD (mg/L O)	417	851	627	149.90
EC (mS/m)	76.90	96.20	82.53	5.41
Free and Saline Ammonia (mg/L N)	30.25	43.06	36.02	4.06
Nitrate + Nitrite (mg/L N)	0.03	0.34	0.09	0.10
pH	6.67	7.96	7.66	0.39
Phosphate (Ortho) (mg/L P)	2.80	3.59	3.07	0.28
Sulphate (mg/L SO_4^{2-})	38.1	48.81	44.57	3.06
Total Dissolved Solids (mg/L)	512	645	551	37.84
Total Kjeldahl Nitrogen (mg/L N)	46	30	41	6
Total Suspended Solids (mg/L)	283	389	319	34.20

COD and Nutrient Removal in BNRAS compartments.

2.2. Vetiveria zizanioides

Zizanioides has stiff and erect stems which can stand up to high velocity flows; it has a thick growth that forms a living porous barrier, which acts as a very effective filter, trapping both fine and coarse sediment (Ralph and Truong, 2004). Vetiver grass is a fast growing, tall, perennial, tropical plant. It has massive and complex root system, which penetrates to deeper layers of soil. It forms a dense layer when planted closely in rows (Yehua et al., 2000). Vetiver grass was first recognized early in the 1990′s for having a 'super absorbent' characteristic that could be effectively used for the treatment of wastewater and leachates generated from landfill in Queensland. Vetiver has high water use rate and tolerant to elevated levels of agrochemicals and heavy metal waste (Ralph and Truong, 2004). *Vetiveria Zizanioides* produces seed that germinates under normal field condition; it is multiplied by division of rhizomes (Hanping et al., 2004).

2.3. *Wastewater*

Module 9 of the DWWTW which uses external nitrification (Muller et al., 2004) was adopted for this study. Wastewater was abstracted from the 3 compartments of the External Nitrification BNRAS (Fig. 3); this was pumped batch-wise using RYOBI pumping machine into the pilot VSBCW (Fig. 2). The wastewater was analyzed for characterization and performance evaluation of the system. Sampling was done at three days interval for 30 days. Samples were collected using standard procedures before screening (raw wastewater), in the 3 compartments of the BNRAS and effluents from the VSBCW (Fig. 3).

2.4. *Analysis*

The measurement of physico-chemical parameters like Total Alkalinity, Chemical Oxygen Demand (COD), pH, electrical conductivity, free and saline ammonia, nitrate, ortho phosphate, sulphate, Total Dissolved Solids (TDS), Total Suspended Solids (TSS) and Total Kjeldahl Nitrogen were carried out using standard methods (APHA, 2005).The DWWTW laboratory was used for all the analysis. Three replicate samples were taken for each of the sampling point and the mean values were used in the analyses. The test was repeated in some cases to control for errors.

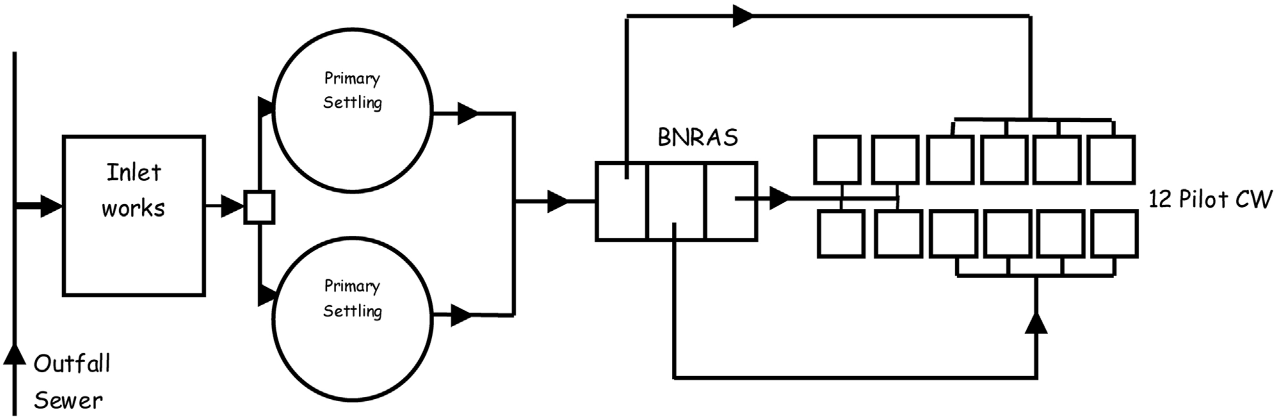

Fig. 3. Schematic diagram of the BNRAS and the VSBCW.

Table 2
Average characteristics of wastewater from the BNRAS compartments before and after treatment in VSBCW.

Anaerobic compartment*	Before treatment	After Treatment (days)				
Parameters		6	12	18	24	30
pH	7.56	6.99	7.05	6.49	7.13	7.30
COD (mg/L)	2046	236	101	93	85	68
FREE & SALINE AMMONIA (mg/L)	25.76	5.57	4.81	4.67	4.17	3.84
TKN (mg/L)	97.90	19.40	17.22	8.45	8.30	3.51
TSS (mg/L)	675	45	22.20	21.20	20.80	11.20
Anoxic compartment						
pH	7.45	7.23	6.83	7.25	7.13	7.18
COD (mg/L)	2118	146	142	108	85	65
FREE & SALINE AMMONIA (mg/L)	10.67	1.21	4.67	0.35	0.46	0.38
TKN (mg/L)	139.40	7.93	5.96	2.37	8.30	3.06
TSS (mg/L)	1718	36.40	22.20	12	8.80	4.80
Aerobic compartment						
pH	7.40	6.92	7.21	7.11	7.11	7.23
COD (mg/L)	2076	163	140	107	86	61
FREE & SALINE AMMONIA (mg/L)	8.90	7.10	5.26	5.30	4.07	0.68
TKN (mg/L)	132	51.95	9.20	9.99	0.87	2.12
TSS (mg/L)	1998	35.40	27.20	25.20	21.30	9.60

*Effluent from the primary sedimentation tank mixed with return sludge from the secondary sedimentation tank.

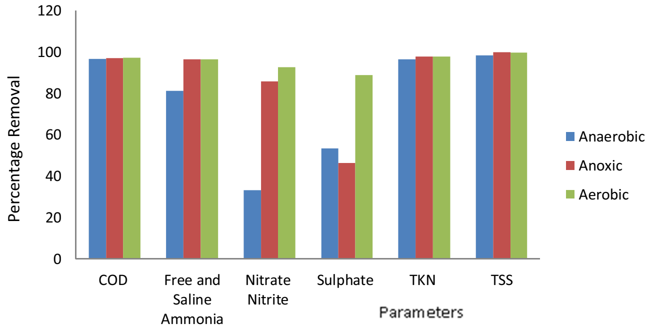

Fig. 4. Percentage removal efficiency of VSBCW fed with effluent from the compartments of the BNRAS after 30 days.

3. Results and discussion

3.1. Characterization of wastewater

Sample analyzed during the period for the raw wastewater had mean values and standard deviation shown in Table 1. Pollution parameters in the wastewater displayed considerable variability in concentration throughout the study period. These variations are consistent with reported variability of pollutant concentration in wastewater within individual sites (Bilgin et al., 2014; Brix and Arias, 2005). The wastewater could be characterized as municipal (Metcalf and Eddy, 2004; Muller et al., 2004).

Rapid drop was observed in the COD values of the effluent in the VSBCW after 6 days retention period. The effluent from the anoxic zone of the BNRAS has the highest removal efficiency of 93.11% within the first 6 days of treatment while the effluent from the Anaerobic and Aerobic zones of the BNRAS has a removal efficiency of 88.47% and 92.15% respectively (Table 2). The removal efficiency of the VSBCW proceeded at an average rate of 23.43, 17.88 and 21.75% in the wastewater from the anaerobic, anoxic and aerobic compartments of the BNRAS respectively. The effluent from the anaerobic zone has an initial low rate of removal compared to the other two zones but has the highest average removal efficiency as the treatment progresses. The treatment of effluent from the anaerobic zone which consists of returned activated sludge and effluent from the primary sedimentation tank was found to have the highest percentage removal percentage during the 30 days retention period in the VSBCW. The percentage removal efficiency was found to be 97.21% (Fig. 4). This showed that the microbial activity at this zone was much, the microbes been supplied by the returned activated sludge from the secondary sedimentation tank (Akratos and Tsihrintzis, 2007; Babatunde et al., 2008).

A reasonable decrease was also notices in the Free and Saline Ammonia after 6 days of treatment in the VSBCW for the anaerobic, anoxic zones with percentage reduction of 78.38 and 88.66% however the aerobic zone has a percentage removal of 20.22%. The percentage reduction in free and saline ammonia that occurred within 6 days retention period in the VSBCW was more than the reduction of 65.48% that took place in the movement from the anaerobic zone to the aerobic zone within the BNRAS. Bigambo and Mayo (2005) opined that nitrogen removal in CW is mainly due to the microorganisms in the roots of plants. The relative amount of carbon sources in a CW system, usually represented by C/N ratio has been shown to determine the nitrogen removal/conversion rates (Zhu et al., 2015; Li et al., 2015). According to Bigambo and Mayo (2005) attached biofilm layers on different parts of macrophytes and substrate affects the nitrogen removal rate.

Studies have shown that the potential for denitrification is specific for different plants species (Bastviken et al., 2009). This study revealed a Nitrate/Nitrite percentage reduction of 33.33, 85.71 and 92.48% in the anaerobic, anoxic and aerobic processes respectively. This agrees with Akratos and Tsihrintzis (2007) that the removal of Nitrogen in CW systems is always lower than those for organic loading.

In CW, suspended solids are removed by natural/physical wetland process. According to Brisson and Chazarenc, (2009) the physical mechanism for suspended solids removal includes flocculation/sedimentation and filtration/interception. At the early stage of treatment, a higher percentage removal of TSS was observed with an initial percentage of 93.3, 97.88 and 98.22% in the anaerobic, anoxic and aerobic zones respectively after 6 days retention period. The treatment proceeded at an average of 16.67, 39.27 and 25.23% in the anaerobic, anoxic and aerobic zones respectively during the 30 days experimental period. Fig. 4 showed that the VSBCW removed 98.34, 99.72 and 99.6% of TSS in the wastewater from the anaerobic, anoxic and aerobic zones of the BNRAS respectively.

4. Conclusion

The findings from the sequential BNRAS/VSBCW investigated in this study have shown that incorporating a VSBCW into a BNRAS improves the treatment efficiency of a BNRAS system. Using a VSBCW immediately after the anaerobic zone of the BNRAS largely reduces the Chemical Oxygen Demand. The return activated sludge from the sedimentation tank improves the performance of the VSBCW. The combination was also able to remove nutrients and suspended solids in municipal wastewater. The study revealed that incorporating a VSBCW using locally available macrophytes into a BNRAS provides a less resource intensive and sustainable system that can reduce the cost of operating a BNRAS system.

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