ASSESSING THE EFFICIENCY OF SUBSURFACE CONSTRUCTED WETLANDS PLANTED WITH DIFFERENT MACROPHYTES IN REMOVING HEAVY METALS FROM WASTEWATER

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Abstract

This study was undertaken to assess the efficiency of macrophyte plants in removing heavy metal in municipal wastewater using laboratory scale quarry dust vertical constructed subsurface wetlands. Plants used were *Typha latifolia, Phragmites australis* and *Polygonam spp*. The control treatment was not vegetated. The parameters evaluated were the concentration of lead, cadmium and zinc in the influent and effluent sewage after different retention periods in the wetland. At the end of experiment the macrophytes were harvested and the concentration of the heavy metals in shoots and roots determined. *Polygonam spp.* absorbed highest amounts of Zinc while *Phragmites australis* absorbed the highest amount of lead and cadmium. The roots had a higher concentration of the heavy metals than the shoots. Planted beds differed in the removal rates of the heavy metals which were found to be dependent on the plant species. The percentage removal of the heavy metals from the raw sewage by the vegetated system was 87%, 83% and 84% for lead, cadmium and zinc respectively after a retention period of 8 days. The control surprisingly showed a percentage removal in excess of 60%, indicating that the removal of heavy metals was mainly accomplished by the quarry dust medium. The concentrations of the three heavy metals in the effluent sewage were all below the maximum allowable concentrations for discharge into the environment. The constructed wetlands were therefore effective in reducing the heavy metals concentrations from the raw sewage to tolerable levels.

Key words: constructed wetlands, wastewater, macrophytes, heavy metals, quarry dust

1.0 Introduction

Among the major challenges facing developing countries is the need to ensure on-going provision of the basic human service of sanitation. The replications of centralized, highly engineered human waste management systems, resultant of sanitary reforms of the 19th century have not been successful in many developing countries (Rose, 1999). This is largely due to lack of resources to construct and maintain such treatment facilities. The solution to this scenario requires innovative and sustainable approaches that are appropriate for protecting public health, recovering nutrient resources and protecting water resources from pollution.

What is becoming relevant and appropriate are the alternative low cost and effective wastewater treatment systems like the constructed wetland, which also promotes the recovery and reuse of wastewater resources. This way, wastewater treatment is transformed from a disposal-based linear systems (which is expensive in the long run) to a recovery based closed-loop system that promotes conservation of water and nutrient resources and contributes to improved public health (Edward and Martin, 1991; Rose, 1999).

Alternative technologies to conventional wastewater management have been found to be environmentally sound and economically viable approach to waste water management. Constructed wetlands for example have contributed to providing low cost sanitation in the developed temperate countries. Constructed wetlands have been found to have lower construction and maintenance costs and require low skilled labor for operation when compared to the conventional treatment systems. A limited database supports the capability of the subsurface flow wetland process for effective removal of metals and other priority pollutants (Kovacic *et al*., 2006; Reed, 2000; Reed *et al*., 1987). It is thus important to establish through continued experimentation, the utility of constructed wetlands in the removal of heavy metals.

There are two types of constructed wetlands: vegetated sub-surface flow and free surface flow. Free water surface (FWS) constructed wetlands closely resemble natural wetlands in appearance and function, with a combination of open-water areas, emergent vegetation, varying water depths, and other typical wetland features. A typical FWS constructed wetland consists of several components that may be modified among various applications but retain essentially the same features. These components include berms to enclose the treatment cells, inlet structures that regulate and distribute influent wastewater evenly for optimum treatment, various combinations of open-water areas and fully vegetated surface areas, and outlet structures that complement the even distribution provided by inlet structures and allow adjustment of water levels within the treatment cell. Shape, size, and complexity of design often are functions of site characteristics rather than preconceived design criteria

Subsurface flow (SF) constructed wetlands first emerged as a wastewater treatment technology in western Europe based on research by Seidel (1996) commencing in the 1960's, and by Kickuth (1977) in the late 1970's and early 1980's. Early developmental work in the United States commenced in the early 1980's with the research of Wolverton *et al.,* (1983) and Gersberg *et al.,* (1985).

The SF concept developed by Seidel included a series of beds composed of sand or gravel supporting emergent aquatic vegetation such as cattails(*typha*), bulrush(*scirpus*), and reeds(*phragmites*), with *phragmites* being the most commonly used. In the majority of cases, the flow path was vertical through each cell to an underlain and then onto the next cell. Excellent performance for removal of BOD_5, TSS, nitrogen, phosphorous, and more complex organics was claimed. Pilot studies of the concept in the United States were marginally successful, and it has not been utilized in recent years.

Kickuth (1977) proposed the use of cohesive soils instead of sand or gravel; the vegetation of preference was *phragmites* and the design flow path was horizontal through the soil media. Kickuth's theory suggested that the growth, development and death of the plant roots and rhizomes would open up flow channels, to a depth of about 0.6 m in the cohesive soil, so that the hydraulic conductivity of a clay-like soil would gradually be converted to the equivalent of a sandy soil. This would permit flow through the media at reasonable rates and would also take advantage of the adsorptive capacity of the soil for phosphorus and other materials. Very effective removal of BOD_5, TSS, nitrogen, phosphorus, and more complex organics was claimed. As a result, by 1990 about 500 of these "reed bed" or "root zone" systems have been constructed in Germany, Denmark, Austria, and Switzerland. The types of systems in operation include on-site single family units as well as larger systems treating municipal and industrial wastewaters. Many of the early systems were designed with a criterion of 2.2 m^2 of bed surface area per population equivalent (PE) (Boon, 1985). A PE in European terms is equivalent to the organic loading from one person, or approximately 0.04 kg/d BOD_5 in typical primary effluent. That is equal to a surface organic loading of about 180 kg/ha/d. The more recently constructed systems in Europe (European design and operation, 1990) have been designed for 5 to 10 m^2/PE (40-80kg/ha/d). The hydraulic loading at 5 m^2/PE(at an assumed 0.2m^3/d/PE) would be about 4 cm/d, which, in a commonly used term in the U.S., is equivalent to 23 acres/mgd of design flow, and would provide a hydraulic residence time (HRT) of about six days. For comparison, FWS wetlands in Europe are typically designed at 10 m^2/PE, which results in a surface area about twice that required for the SF type (Brix *et al*., 1992).

Two experiments were therefore conducted to evaluate capability of constructed wetlands in quarry dust medium planted with reeds (*Phragmites australis*), cattails (*Typha latifolia*) and smart water weed (*Poligonam spp*.) in removing lead, cadmium and zinc from raw sewage.

2.0 Methodology

Twelve normal washing basins were modified so as to be used in the experiment. The basins were fitted with a valve socket, plugged from inside, a few centimeters from the bottom and steel cap was used to close the socket. Quarry dust in the form of ¼" gravel was used as the filter media. The dust was placed in the basins to a depth of 5 cm. The first experiment tested cattails (*Typha latifolia*) smart water weed (*Poligonam spp*.) and as the wetland plants, while the second experiment was run with reeds (*Phragmites australis*) as the test wetland plant. The plants were planted in the basins in three replicates with each model having six plants. Three controls (where no plants planted) for the experiment were set up (Figure 1).

Figure 1: Experimental setup during the first experiment: reeds, cattails, smart weeds and control

The plants were then fed with normal water to stabilize the root systems of the plants. This was done for a period of 4 weeks. After stabilizing the normal water was replaced with raw effluent from the secondary stabilization pond of Thika sewerage treatment plant. The whole setup was placed under a roof to avoid dilution of influent by rain water and to avoid excess evaporation.

During the first experiment, effluent from each wet land was collected from each basin after 2,4,6 and 8 days and the concentration of lead (PB, cadmium (CD) and zinc determined using the atmospheric absorption spectrophotometer (AAS) machine following the normal process. In addition plants were also harvested before and after use in the constructed wetlands, dried in an oven, incinerated in a furnace and the ash tested for Pb, Cd and Zn concentration using the AAS machine following the normal procedures.

During the second experiment, effluent from the wetlands was collected from each basin after 2, 4, 6 and 8 days and the concentration of lead (Pb), cadmium (Cd) and Zinc (Zn) determined using the Atomic Absorption Spectrophotometer (AAS) machine following the normal procedures. At the time of sampling the plants had fully established as shown in Figure 2.

Figure 2: Fully established reeds during the second experiment

3.0 Results and Discussion

Experiment 1

The concentration of the heavy metals in the raw sewage and river water at the beginning of the two sampling cycles is shown in Table 1. The concentration differed between the two cycles of research with a higher concentration of Pb and Cd being higher in the first cycle than the final cycle of sampling. This can be attributed to higher industrial activities at the first cycle than the final period. The results from river effluents for the two cycles differ with a higher concentration in the first cycle. Zinc concentration in the raw effluents registered a higher concentration in the final cycle than in the first cycle but the river effluent in the final cycle showed a low concentration of the same than for the first.

Experiment 2

Table 5 shows lead concentration in raw sewage and in the effluent from the constructed wetlands after different retention periods. The table indicates increased Pb removal with the retention time. After 8 days retention, 87.7% of the lead in the original raw sewage had been removed. Though the final effluent concentration was higher that NEMA recommendations of 0.01 mg/L, it was however lower than the current effluent quality from the Thika treatment plant which stands at 0.26 mg/L.

Table 5: Lead (Pb) concentration in the raw and effluent sewage after different retention periods and the corresponding % removal

Retention period (days)	Concentration (mg/l) wetland effluent	Maximum allowable value (mg/l)	Raw sewage (mg/l)	**%** removal by wetland
2	0.56	0.01	0.73	23.3
4	0.19	0.01	0.73	74.0
6	0.18	0.01	0.73	75.3
8	0.09	0.01	0.73	87.7

The Cadmium concentration in the raw sewage and after retentions periods of 2,4,6 and 8 days in the wetlands is presented in Table 6. The Cd concentration was marginally above the NEMA maximum recommended levels. The % removal increased with retention period reaching 83.3% after 8 days. Even for a retention period of 2 days, the effluent from the constructed wetlands was below the maximum level set by NEMA of 0.010 mg/L. The Cd concentration in the effluent from Thika wastewater treatment plant at the time of sampling was 0.011 mg/L indicating minimal removal by the plant.

Table 6: Cadmium (Cd) concentration in the raw and effluent sewage after different retention periods and the corresponding % removal

Retention period (days)	Concentration (mg/l) wetland effluent	Maximum allowable value (mg/l)	Raw sewage (mg/l)	% removal by wetland
2	0.0066	0.01	0.0113	41.6
4	0.0044	0.01	0.0113	61.1
6	0.0025	0.01	0.0113	77.9
8	0.0019	0.01	0.0113	83.2

In the case of Zinc, the removal % by the constructed wetlands was generally lower than for Pb and Cd (Table 7). After 8 days retention period, the % removal was only 70.4. This removal rate was much lower than Gersberg et al. (1985) obtained in the Santee research (USA). They obtained a 97% removal after 5.5 days retention. The low retention our experiment could have been caused the small size of the wetlands. However, the Zn concentration even in the raw sewage was lower than the maximum level recommended by NEMA of 0.5 mg/L. Zinc concentration in the effluent is therefore not a serious concern as of now.

Table 7: Zinc (Zn) concentration in the raw and effluent sewage after different retention periods and the corresponding % removal

Sampling interval(days)	Concentration (mg/l) wetland effluent	Max allowable value (mg/l)	Raw sewage (mg/l)	**%**removal by wetland
2	0.015	0.5	0.027	44.4
4	0.013	0.5	0.027	51.9
6	0.011	0.5	0.027	59.3
8	0.008	0.5	0.027	70.4

Table 1: Heavy metal concentration (mg/L) of the raw sewage from Thika and in the river water

	Lead1st cycle	Lead final cycle	Cadmium 1st cycle	Cadmium final cycle	Zinc 1st cycle	Zinc final cycle
Raw sewage	1.0825	0.1183	0.7561	0.1250	0.7920	0.9944
River	0.4012	0.0189	0.2661	0.0152	0.3740	0.0665

Table 2 shows the concentration of the heavy metals in various macrophytes that were used in the wetland before their establishment and their results after harvest. The initial concentrations of the heavy metals differed between the plants as they were collected from different sites. The after harvest results indicate absorption of the heavy metals by the three plant species. The concentrations increased by as 95 times for lead in *Polygonam spp*., 31 times for Cadmium in *Phragmites australis* and over 250 times for Zinc in *Polygonam spp*. This indicates high ability by these plants to uptake the heavy metals. The uptake is however dependent on the plant species.

Table 2: Zinc, Cadmium and Lead concentrations (mg/L) before and after their use in the constructed wetland

Macrophyte	Lead		Cadmium		Zinc	
	Before sampling	After sampling	Before sampling	After sampling	Before sampling	After sampling
Phragmites australis	0.0007	0.0096	0.0003	0.0094	0.0039	0.3098
Typha latifolia	0.0001	0.0079	0.0018	0.0089	0.0068	0.2553
Polygonam spp.	0.0006	0.0057	0.0005	0.0073	0.0021	0.5292

The difference in the removal rates in the macrophytes in the wetlands could be due to difference in the affinities for the lead by the macrophytes and probably the different root densities of the different plants (Table 3).

Table 3: Levels of Pb, Cd and Zn in mg/L in the roots of the macrophytes used in the wetland

	Phragmites australis			*Typha latifolia*			*Polygonam spp.*		
	Pb	Cd	Zn	Pb	Cd	Zn	Pb	Cd	Zn
Plant roots	0.0096	0.0094	0.3098	0.0079	0.0089	0.2553	0.0057	0.0073	0.5292

Table 4 summarizes the performance of the wetlands planted with the three macrophytes in terms of effluent quality during the first and second cycle. The three macrophytes showed similar trends in the % removal of lead with values of 90.3, 89.4 and 90.8 for *Typha latifolia*, *Polygonam spp*. and *Phragmites australis* respectively during the second cycle. The corresponding values for Cadmium were 91, 89, and 92 respectively. The % removal of Zinc was however higher at 97.5, 978 and 97.5 for *Typha latifolia*, *Polygonam spp*. and *Phragmites australis* respectively. These high removals indicate the possible utility of constructed wetlands as alternative wastewater treatment systems. The control treatment (without plants) is seen to exhibit a relatively high % removal of the heavy metals with 67, 68 and 63% removal for lead, cadmium and zinc respectively. This indicates that the plant removed on average 25% of the heavy metals. The role of the filter media is therefore very significant.

Table 4: The performance of the wetlands planted with different macrophytes during the two sampling cycles

Sample	*Typha latifolia*		*polygonam spp*		*phragmites australis*		Max. allow.	%removal-control
	cycle 1	cycle 2	cycle 1	cycle 2	cycle 1	cycle 2		
Control	0.3548	0.0152					**0.01**	67.23
Lead :1st sampling.	0.2349	0.011	0.3111	0.0126	0.259	0.0111		
Lead :2nd sampling.	0.2268	0.012	0.2546	0.0124	0.2308	0.0106		
Average concentration.	0.23085	0.0115	0.2828	0.0125	0.2449	0.0108		
Raw sewage concentration.	1.0825	0.1183	1.0825	0.1183	1.0825	0.1183		
% rate of removal	78.7	90.3	73.9	89.4	77.4	90.8		
Control	0.2041	0.0169					**0.01**	68.25
Cadmium :1st sampling.	0.2255	0.0114	0.1715	0.014	0.2102	0.0099		
Cadmium :2nd sampling.	0.1147	0.0111	0.1331	0.0131	0.0986	0.0099		
Average concentration.	0.1701	0.0113	0.1523	0.0136	0.1544	0.0099		
Raw sewage concentration.	0.7561	0.125	0.7561	0.125	0.7561	0.125		
% rate of removal	77.51	91	79.86	89.16	79.58	92.08		
Control	0.2917	0.1118					**0.5**	63.17
Zinc : 1st sampling.	0.2631	0.0233	0.2505	0.0197	0.2832	0.0265		
Zinc :2nd sampling.	0.2296	0.0269	0.18	0.0199	0.201	0.0244		
Average concentration.	0.24635	0.0251	0.2153	0.0198	0.2421	0.0255		
Raw sewage concentration.	0.792	0.9944	0.792	0.9944	0.792	0.9944		
% rate of removal	68.9	97.5	72.82	98	69.43	97.45		

4.0 Conclusions

The results of this study have shown that wetlands are suitable alternatives for the treatment of wastewater. The rate of removal varied according to the plant species in the wetland. *Typha latifolia* and *Phragmites australis* were found to have high removal rates for lead. *Typha latifolia* had removal rates >78% during the first cycle and *Phragmites australis* had >90% removal rate during the final cycle. The combination of reed and *Typha latifolia* is considered to have a better removal and affinity for lead.

Phragmites australis bed was found to remove high amounts of the cadmium metal. The rate of removal was found to be > 72% and 86% for the first and second sampling periods of the first cycle. In the final cycle it was found to be 92.08% for both the sampling periods. Reed is then concluded that it is better alternative for the removal of cadmium, (Table 5 and 6).

Polygonam spp. had a higher removal rate for Zinc metal with removal rates of 68.37% and 77.27% for the 1st and 2nd sampling periods of the first cycle. The final cycle rates for Polygonam spp. were 98.02% and 98% for 1st and 2nd sampling periods respectively. Therefore *Polygonam spp.* is concluded to have better removal rates for zinc metal and should be used in the removal of the Zinc in wastewater.

Therefore, *Phragmites australis, Typha latifolia and Polygonam spp.* have the potential in remediating sites that contain high concentration of Pb, Cd and Zn. The filter media was found to take a major part in the removal of the heavy metals when compared to macrophytes which generally had lesser uptakes of heavy metals. This indicates that the filter media has a significant role in the removal of the heavy metals in wastewater. There is difference between the uptakes of the metal ions by the macrophytes. The plant roots play a major role in the uptake as compared to the shoot uptake as higher concentration is found to be in the roots.

Bearing in mind that the filter media acts as a sink for heavy metals, it would suffice that there would be exhaustion of the exchange sites, and thus reduced utility with time. However, they can be used in polishing of treated waste water from conventional treatment plants, or as stand-alone plant.

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