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Research Paper

Efficacy of Hydroponic and Soil-Based Vetiver Systems in the Treatment of Domestic Wastewater

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Abstract: *Conventional wastewater treatment technologies are deemed to be either ineffective or costly for developing countries such as Kenya. This has led to extensive research in phyto-remediation; the use of aquatic plants such as vetiver grass to reduce pollutant levels in wastewaters. This paper describes the comparative performance of vetiver grass systems in the treatment of domestic wastewater when the plant is established using three different techniques: in a soil medium (soil-based system), with roots suspended in water (hydroponic system) and as a hybrid of these two. Three experimental units of dimensions 1.0 x 0.6 x 0.4m (length x width x depth) fabricated from sheet metal and established with 120 vetiver plants using the three techniques were involved. They were administered with post-septic tank domestic wastewater whose levels of* BOD_5*, TSS, TN and TP were measured prior to application, and five days after. The results indicated that generally, the soil-based vetiver system achieved the highest reduction in pollutant levels, followed by the hybrid and the hydroponic systems. For instance, in case of* $BOD_{5,}$ *the soil-based, the hybrid, the hydroponic and the control units achieved 75.12, 68.44, 65.64 and 37.66 percentage reduction rates respectively. Analysis of variance at 5% significant level and the comparison of means by the least significance difference (LSD) test at* $P < 0.05$ *consistently indicated the existence of significant differences between the vetiver treatments and the control, and between the soil-based vetiver system and the others. The major findings were that both the soil medium and the vetiver plants play a major role in wastewater remediation. Based on these findings, it was concluded that constructed wetland vetiver systems should preferably involve a suitable solid growth medium.*

Keywords: Vetiver, wastewater treatment, soil-based, hydroponic, hybrid, BOD, TN).

1. Introduction

Wastewater treatment is virtually mandatory in the modern world to simultaneously address the key problems of water scarcity and environmental degradation. In Kenya, the National Environmental Management Authority (NEMA) is the body in charge of environmental regulation and demands that water discharged into the environment must meet its acceptable quality standards. Since conventional treatment technologies are either ineffective or wasteful and costly (Nhapi, 2004; Oron, 1994) many studies on phyto-remediation technologies are ongoing. Of the many plant species that have been widely studied, vetiver grass (*vetiveria zizanioides*) has been identified to be of significant potential (Njau and Mlay, 2003; Liao *et al.*, 2003). Vetiver constructed wetlands are hence the one of the best alternatives to the current wastewater treatment technologies. The range of wastewater treatment technologies in use currently is wide, from simple stabilization ponds through septic tanks to the highly sophisticated and efficient containerized "package plant" systems, which are expensive, power dependent and requiring expert maintenance (Nhapi, 2004; de Mowbray, 2009). Consequently the problem of inadequate and inefficient sewerage system is profound in Kenya, extending to virtually all the major towns. Only 14% of the population living in 215 urban areas in Kenya is reported to be covered by sewerage systems (NWMAS, 2008). Along the Kenyan coastline there are many towns and social establishments which are actively contributing to the problem of marine pollution, threatening the delicate marine ecosystem and resources. The key coastal town of Mombasa has only 30% of its population covered with the local sewer system (CWSB, 2008), while Kilifi town has no centralized sewer system. By the year 2007, it was estimated that Mombasa town alone needed sh. 20 billion annually to handle its then daily sewage output of 160,000 cubic meters (CWSB, 2008). Many small Kenyan towns such as Kilifi still rely on septic tanks which have limited capacities to contain the sewage generated within them. According to King (2000), an appropriate remedy to this is the development of small efficient onsite treatment systems. Matters are worsened on noting that voluminous amounts of valuable wastewater are being wasted together with recoverable agricultural nutrients in form nitrogen and phosphorous. This happens despite the fact that the lower coastal region of Kenya is largely semi arid with soils of low fertility (MoPND, 2002). To address these concerns, approaches that incorporate re-use and recovery measures need to be adopted, one of such being the use of aquatic plants.

1.1 Role of Aquatic Plants

The use of aquatic plants in wastewater treatment is becoming increasingly common in wastewater management approaches that integrate treatment, recycling and reuse. Such approaches enhance the aspects of efficiency and sustainability in addressing the problem of wastewater management. Acquatic plants serve to absorb pollutant compounds in the wastewater while enabling nutrient reclamation options (Nhapi, 2004; Hart *et al.*, 2003; Lasat, 2002; Oron, 1994). As noted by de Mowbray (2009), both natural and constructed wetlands have been used extensively throughout the world for over 30 years and found to be appropriate for the developing world as they produce effluents that meet prescribed standards. As a wastewater treatment technology, phyto-remediation is environmental friendly, inexpensive and can be carried out at the point of pollution. Dingles (1982) classified the plants employed into three classes ie submerged algae and plants, floating macrophytes and emergent vegetation. He noted that the floating macrophytes (duckweeds, water ferns among others) use atmospheric oxygen and carbon dioxide but obtain the remaining nutrients from the wastewater. Their roots provide a substrate on which the heterotrophic microorganisms grow. Most reductions in the levels of TSS and BOD are reported to be due to settlement rather than biological activity by Gray (2009); who explained that the plants not only exhibit a luxury uptake of nutrients but also accumulate other components from wastewater such as the heavy metals and synthetic organic compounds. Consequently a greater reduction is achieved in the concentration of wastewater constituents and in the volume of residual material to be disposed of. Additionally, useful plant and animal protein is obtained on harvesting the plants (Linsley and Franzini, 1979). Different plants have been evaluted for this function including typha grass (*typha latifolia*), nile cabbage (*pistia stratiote*), papyrus (*cyperus papyrus*), duckweed (*lemna species*) vetiver grass (*vetiveria zizanioides*) among others. Of the many plant species that have been evaluated for their abilities to treat wastewater, vetiver grass has consistently performed exceptionally well (Njau and Mlay, 2003; Liao *et al.*, 2003).

1.2 The Vetiver Grass System

The vetiver grass system is a technology that employs the vetiver grass (*Vetiveria zizanioides*) for various environmental management applications. This grass is a C_4 perennial grass with origins in India but not prevalent in Kenya. Owing to its unique morphological and physiological characteristics that make it tolerant to many adverse climatic and edaphic conditions, it has been successfully introduced for trials in Kenya (Owino, 2002). The grass exhibits both xerophytic and a hydrophytic characteristics (Njau and Mlay, 2003), although it optimally thrives in waterlogged habitats (Boonsong and Chansiri, 2005). Ta-oun *et al.*,(2003) showed that it can grow in wastewater at different depths of 5-15 cm within 6 months. It has an exceptionally wide pH range, with the potential to grow in any type of soil, withstand extreme drought and thrive under temperatures as low as -9^o centigrade (Njau and Mlay, 2003). Its ability to absorb and tolerate elevated levels of nitrogen and a high dry matter production rate been reported (Wagner, 2003; Mayorca, 2007; Ash and Truong, 2003; Cameron et. al., 2003). It is propagated by root divisions, or slips.

The performance of Vetiver Constructed Wetlands (VCW) in wastewater treatment has been found to be commendable. Zheng *et al*., (1997), confirmed that the VCW is a good purifier of eutrophic water. It has been reported to reduce septic plant effluents' by 99% nitrogen, 85% phosphorous and 95% faecal coliforms reduction (Ash and Truong, 2003). Studies regarding the use of vetiver plants in the treatment of different types of wastewater have been mainly done using either the hydroponic or the soil-based techniques of planting, albeit with conflicting findings. Trials on vetiver by Hart *et al.,(* 2004) indicated that on-site hydroponic vetiver treatment of domestic effluent had the potential of being more effective than other such treatments, and that hydroponic vetiver reduces far more nitrogen and phosphorous than any other plants. In contrast to this, studies by Mng'anya *et al*.(2001), Bonsoon and Chansiri (2005) and Headley and Tanner (2006) indicated that hydroponic techniques posted lower nitrogen and phosphorus removal efficiencies when compared with results from other studies which had soils as a growth medium. By evaluating the performance of vetiver across three distinct planting techniques, this research aimed at yielding preliminary information related to the comparative abilities of the vetiver systems to treat wastewater.

2.0 Materials and Methods

2.1 Experimental Materials

The main experimental materials used were vetiver plants, sandy soil from the locality and domestic wastewater collected from the septic tanks of the college. The soil, which was predominantly of the coral limestone sand type, had a porosity of 0.35 and pH value of 5.8. The vetiver plant tillers were sourced from the Kenya Agricultural Research Institute (KARI) station at Mtwapa in the Kilifi County. They were positively identified to be of the species *Vetiveria zizanioides.*

2.2 Experimental Site and Set-up

The research was conducted at the Pwani University College flower nursery farm between 15^{th} August and 30^{th} September, 2009. The college is located in the coastal town of Kilifi which lies 62 km to the North of Mombasa town, on latitudes 2^{o} South and longitudes 40^{o} East.

Treatment units mimicking constructed wetlands were designed by assuming first order kinetics and plug flow reaction conditions. The surface area of the units was thus determined using the equation:

$$A = \frac{Q\ .\ln\frac{Ce}{Co}}{K_T.Y.n}$$

Where:

n = 35% is the porosity of the soil medium as determined at Pwani University;
Y = 0.4m is the depth of the medium; and
K_T is the temperature dependent first order reaction rate constant.

$$K_T = K_{20} * \theta^{(T-20)}$$

Where:

$\theta = 0.953$ is the temperature correction factor (Tchobanoglous *et al*., 2003); and
K_{20}=0.52 d^{-1} is the temperature dependent first order reaction reference rate constant (Davison *et al*., 2005).

Using the mean minimum temperature of Kilifi of T = 25^{o}C;

$$K_{20} = 0.52 * 0.953^{25-20} = 0.41\ d^{-1}$$

$$A = \frac{0.008 * \ln\frac{100}{10}}{0.41 * 0.4 * 0.35} = 0.32\ m^2$$

Consequently, the treatment unit was sized considering that for plug-flow conditions, the recommended length to width ratios are 3:1 and 5:1 (Headley *et al*., 2005). Using the 3:1 ratio and taking the length (L) to be equal to 1.0m, the width (W) was determined as 0.32m for each treatment unit. Twelve boxes of dimensions 1.0 x 0.3 x 0.45 m dimensions were fabricated from plain sheet metal for use in the establishment of the three vetiver systems and their controls. The 0.05m increment in design height of the box was meant to serve as a freeboard.

The soil-based unit was constructed by filling a box with soil to a depth of 0.4m and planting with 120 vetiver plants in clumps of two tillers spaced 10cm apart. The hydroponic unit was made by suspending the same population of plants into the box from a rectangular meshwork of bamboo sticks. They were attached to the bamboos by loosely tying with a sisal twine. The hybrid unit was constructed by first transversely partitioning the box into two halves using perforated a metallic plate. One half was filled with soil and established with 60 vetivers. The other half was established with 60 vetivers using the hydroponic technique as described above. The control consisted of a similar box with neither the plants nor the soil, to mimic a miniature waste stabilization pond. All these were replicated thrice. The units were each supplied with fourty litres of raw wastewater of known pollutant concentration which was detained for five days.

(a) (b)

Figure 2 (a and b): The treatment units four weeks after transplanting

2.3 Observations and Analysis

The influent and effluent were sampled at five-day intervals and analyzed for BOD (biochemical oxygen demand), TN (Total Nitrogen), TP (total phosphorus) and TSS (total suspended solids) according to standard methods for water and wastewater analysis (Andrew, *et al.*, 2005). The growth rates of shoots were studied in terms of increase in height with time. The collected data were treated with one way analysis of variance (ANOVA) to test for the significant difference between effluent wastewater pollutant levels of the different treatments. The LSD (Least Significance Difference) tests at 5% probability level were evaluated.

3. Results and Discussions

3.1 Total Nitrogen (TN)

Results for quantities of TN removed from wastewater are presented in table 3.1 below.

Table 3.1: Change in TN levels for the five-day contact period

Treatment	Mean initial TN level (mg/L)	Mean level after treatment (mg/L)	% change
Control	45.64	33.71[a]	26.14
Hydroponic	45.64	23.11[b]	49.35
Hybrid	45.64	22.92[b]	49.77
Soil-based	45.64	19.59[c]	57.07
LSD		1.43	

*Means with the same letter in the same column are not significantly different at $\alpha = 0.05$

Statistical analysis indicated that the levels of total nitrogen for the soil-based treatment were significantly lower than all the other treatments at 5% level of significance. All the vetiver based treatments posted significantly lower TN levels than the control. The difference in the levels of TN for the hydroponic and hybrid treatments was insignificant. These findings are depicted graphically in figure 3.1 below.

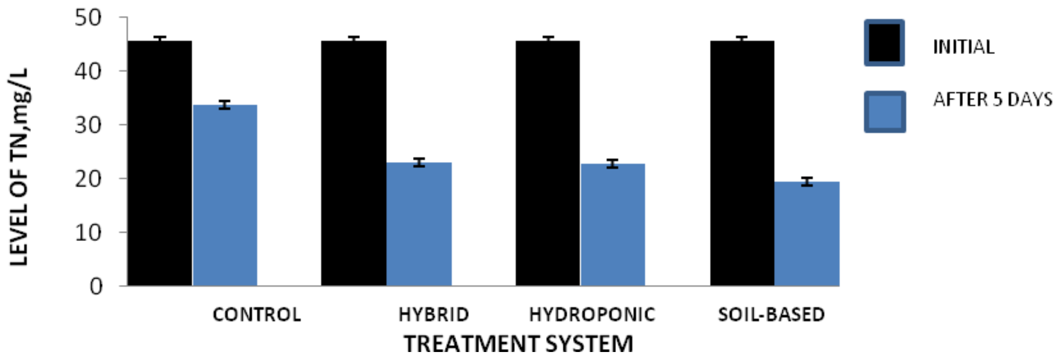

Figure 3.1: TN in the treated wastewaters for a five-day contact period

The mean TN removal rates are however lower than others posted from other researches over the same contact period, such as those by Kantawanichkul *et al* (1999), Njau and Mlay (2003), who recorded removal percentages of up to 90% and 83.8% respectively by constructed wetlands with vetiver grass. These results confirmed that vetiver grass inclusion in the treatments boosts their TN removal efficiency. They also reveal that the soil-based treatment is the most effective, indicative of the role of the soil medium as a matrix for nitrogen adsorption in working to remove TN from wastewater as suggested by Ogombe (2001).

3.2 Total Phosphorous

The results for the removal of total phosphorous (TP) from wastewater revealed a generally poor performance by the systems. This is in conformity with findings from other closely similar works by Boonsong and Chansiri (2005), Njau and Mlay (2003) among others. They noted that generally, vetiver boosts the abilities of aquatic systems to remove phosphorous from wastewater, but the performance remains low. Table 3.2 below shows the percentage TP level reductions.

Table 3.2: Change in TP levels for the five-day contact period

Treatment	Mean initial TP level (mg/L)	Mean level after treatment (mg/L)	% change
Control	6.56	5.59^{a}	14.85
Hydroponic	6.56	4.65^{b}	29.12
Hybrid	6.56	4.64^{b}	29.27
Soil-based	6.56	4.41^{c}	32.90
LSD		0.22	

*Means with the same letter in the same column are not significantly different at $\alpha = 0.05$

The level of TP was least in the soil-based unit (4.41 mg/L) and highest in the control (5.59 mg/L). The achieved TP levels for all the treatments fail to meet the standards of a maximum of 2 mg/L set by EMCA 2006 for wastewater discharges into public water. Statistical analysis revealed that the mean levels of total phosphorus were significantly different at 5% significant level. They were significantly higher between the control than all the rest, and between the soil-based treatment and both the hydroponic and the hybrid. There was no significant difference in the means between the hydroponic and the hybrid treatment. Figure 3.2 below displays these observations.

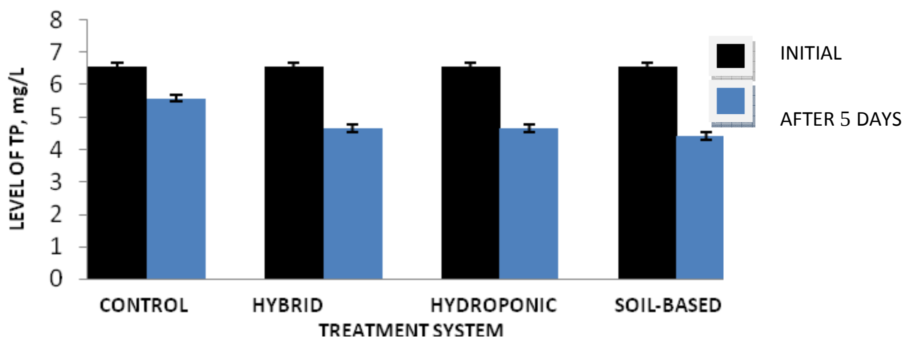

Figure 3.2: TP levels in the treated wastewaters for a five-day contact period

The findings confirm the findings of a host of other researchers regarding phosphorous removal from wastewater by wetlands (Boonsong and Chansiri, 2005; Headly and Tanner, 2006) who concluded that phosphorus is removed from wastewater through the processes of sedimentation and burial, adsorption and precipitation, and exchange processes between soil and the overlying water column with little contribution of absorption by plants. The soil-based treatment therefore availed a bigger medium for burial and adsorption of phosphorus, hence enabling it to perform better. Experimental units planted with vetiver plants achieved lower TP levels than the control units because they could absorb phosphate-P and the vetiver roots could slow water velocity. This increased TP removal through sedimentation of organic phosphorus rather than plant uptake, since past studies show that plants contribute very little in phosphorus removal, only about 3% (Mng'anya *et al.,* 2001). Hence, phosphorous removal is mainly through the processes of sedimentation of particulate phosphorus aided by good substrate porosity and followed by the sorption of soluble phosphorus.

3.3 Biological Oxygen Demand, BOD

The levels of the five day biological oxygen demand, BOD_5, as determined from the wastewater samples from the treatment units after five days are presented in table 3.3 below. They indicate that the mean levels of BOD_5 varied by a wide range from 22.70 mg/L as posted by the subsurface unit to 56.87 for the control. ANOVA at 5% level of significance revealed that the means were significantly different. Separation of means by the LSD measure showed that there were significant differences between any two of the means. The difference in the mean BOD levels between the control treatment mean and the next nearest mean (56.87 and 31.34 mg/L) was considerably high. This indicated the extent of the beneficial effect of including vetiver in biological wastewater treatment systems.

Table 3.3: Change in BOD levels for the five-day contact period

Treatment	Mean initial BOD level (mg/L)	Mean level after treatment (mg/L)	% change
Control	92.67	56.87^{a}	38.67
Hydroponic	92.67	31.34^{b}	66.20
Hybrid	92.67	28.79^{c}	68.95
Soil-based	92.67	22.70^{d}	75.52
LSD		2.29	

*Means with the same letter in the same column are not significantly different at $\alpha = 0.05$

These observations are illustrated graphically in figure 3.3 below.

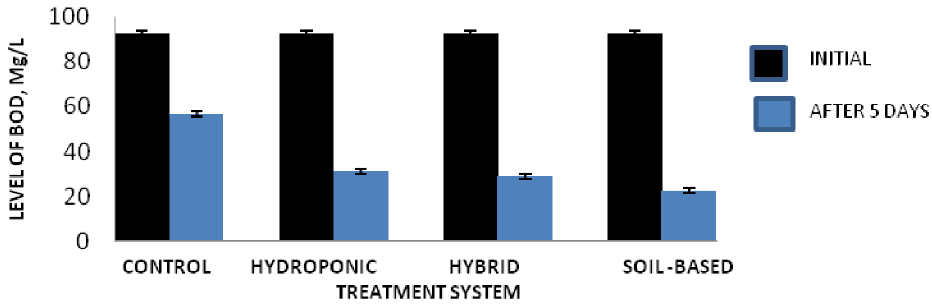

Figure 3.3: BOD levels in the treated wastewaters for a five-day contact period

The results agree with findings by others such as Njau and Mlay (2003), Boonsong and Chansiri (2005) among others. They reported BOD level changes of 67.4 and 91.5 % respectively which compare well with the maximum of 75.2% achieved by the soil-based unit in this research (Table 3.3). The levels of BOD achieved by the hybrid and the soil-based units meet the standards of a maximum 30 mg/L stipulated by Kenyan authorities in EMCA (2006). Njau and Mlay (2003) explained these observations by stating that aquatic plants support the BOD level reduction processes by availing atmospheric oxygen in their submerged stems, roots and tubers, which is then utilized by the microbial decomposers attached to them below the level of the water to digest the organic matter in wastewater. The results also implied that the use of the soil medium impacted positively on the abilities of the units to lower the level of BOD in wastewater, since the hybrid and the soil based units respectively reduced this level by increasingly greater margins. This observation can be attributed to the input of the soil medium in form of either better nutrition for the plants, or playing host to a wider variety of microorganisms that digest the organics (Gray, 2009). The stated better nutrition is evidenced by the relatively faster biomass development observed for the plants in the soil-based units. The differences in plant heights, which was used to infer growth rate, were significantly different at $\alpha = 0.05$. Table 3.8 shows the heights of the plants in the various treatment units at the beginning of each week.

Table 3.8: Plant heights at beginning of each week, in centimetres

Treatment	Plant height, cm						
	wk1	wk2	wk3	wk4	wk5	wk6	Mean
Soil Based	30.0	47.5	61.9	75.8	82.3	97.6	**65.85^{a}**
Hybrid	30.0	41.2	62.1	73.6	80.3	95.9	**63.85^{ab}**
Hydroponic	30.0	38.5	61.2	72.5	78.4	95.1	**62.62^{b}**
LSD							**2.14**

*Means with the same letter are not significantly different at $\alpha = 0.05$

3.4 Total Suspended Solids, TSS

The results for the mean levels of the total suspended solids (TSS) in the wastewater samples after five days are presented in table 3.4 below.

Table 3.4: Change in TSS levels for the five-day contact period

Treatment	Mean initial TSS level (mg/L)	Mean level after treatment (mg/L)	% change
Control	173.66	99.93^{a}	42.46
Hydroponic	173.66	81.32^{b}	53.17
Hybrid	173.66	80.53^{b}	53.63

Soil-based	173.66	73.32[c]	57.78
LSD		4.039	

*Means with the same letter are not significantly different at α = 0.05

Statistical analysis revealed that the mean levels of TSS were significantly different at 5% significance level for the various treatments. The mean for the control was significantly higher relative to the rest of the treatments. The means between the soil-based unit on one hand, and the hydroponic and hybrid treatments on the other, were significantly different too. However the mean TSS difference between the hybrid and the hydroponic treatments was insignificant. Figure 3.4 below graphically illustrates these observations.

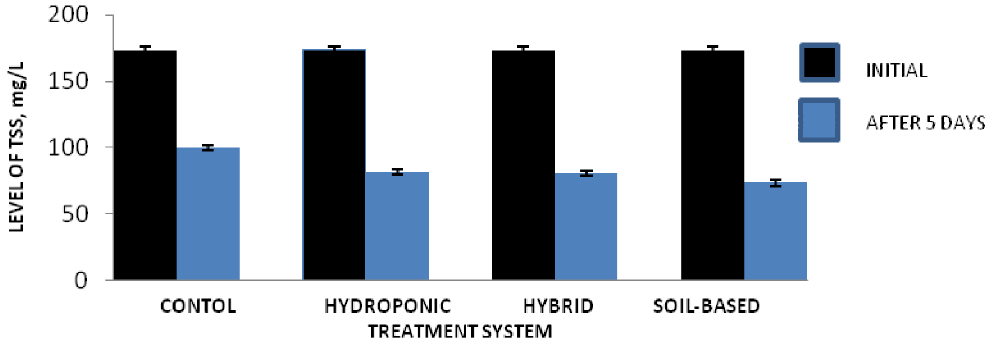

Figure 3.4: TSS levels in the treated wastewaters for a five-day contact period

The results prove that vetiver plants play a significant role in the removal of suspended solids from wastewater. Weiner and Mathews (2007) noted that total suspended solids are removed from secondary domestic wastewater mainly through the processes of settlement and filtration. The better performance exhibited by the vetiver containing units are therefore attributed to the contribution of vetiver roots in the trapping of suspended solids in the wastewater, and for continuous flow systems, the stabilization of the flow. In a study regarding the extent of the trapping of TSS by plant roots, Smith and Kalin (2000) measured the mass of solids trapped amongst roots of a two year old floating *Typha* vegetation mat on an acid mine drainage pond and estimated that a mature system would capture at the least, approximately 2.2 kg of solids per m^2 of floating vegetation. Thus it is no surprise that the units containing vetiver, known to be deep-rooted, posted higher TSS removal efficiency than the control. Significantly lower TSS levels were posted by the soil-based treatment, due to the contribution of the soil medium, which acted as a filter for the solid particles. Njau and Mlay (2003) obtained a mean TSS removal rate of 81.42% compared to 57.60 % posted by the soil-based treatment in this research. The wide variation may be attributed to the differences in the medium (soil) properties, plant density and population. The achieved TSS levels in wastewater are far above the stipulated maximum level of 30 mg/L in EMCA (2006) for wastewater discharges into public water in Kenya.

4. Conclusions

The results of the study confirm that vetiver is a useful tool in wastewater treatment since all the units that contained vetiver plants performed better than the plant less controls. It was also established that soil-based systems perform better in the treatment of domestic wastewater than both the hybrid and the hydroponic systems effectively informing us of the importance of the soil medium. This suggests that whenever possible constructed wetland vetiver wastewater treatment units should include a suitable solid medium.

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