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PERFORMANCE OF VERTICAL AND HORIZONTAL SUBSURFACE-FLOW CONSTRUCTED WETLANDS IN TREATING LEACHATE

[1,*]NAZAITULSHILA R., [2]JOHAN S.

[1]*Department of Engineering Science, Faculty of Science and Technology, Universiti Malaysia Terengganu, 21030 Kuala Terengganu, Terengganu, Malaysia.*
[2]*Department of Environmental Engineering, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor Bahru, Malaysia.*

** Corresponding author e-mail address: nazaitulshila@umt.edu.my*

Abstract: Leachate treatment is the biggest challenge in landfill management. Improper handling of leachate could lead to various environmental and health problems. In recent years, many researchers have been directed to seek effective yet economic approach in treating leachate. Constructed wetland has been identified as one of the most interesting method in leachate treatment. This natural treatment system is more cost-effective than other conventional approaches. It offers comparable treatment performance at lower installation, operation and maintenance cost. In this study, vegetated vertical subsurface-flow (VF-SSF) and horizontal subsurface-flow (HF-SSF) constructed wetland were designed for the treatment of landfill leachate. *Limnocharis flava*, which is emergent, hydrophytic vegetation, was planted at the surface of each constructed wetland system. Leachate was continuously circulating through the SSF constructed wetland systems at constant flow rate of 15 ml/min and 5 hrs/cycle hydraulic retention time (HRT) for 18 days. The findings of this study proposed that the removal of nutrients and heavy metals could occur through soil substrates of wetland and/or perform by *L.flava* bed. Significant improvement in removal efficiency of NH_3^-N, NO_3^-N, Fe and Mn achieved by using VF-SSF and HF-SSF constructed-wetland systems signifies the contribution of *L.flava* plant in enhancing the overall performance of SSF constructed-wetland system. VF-SSF constructed-wetland system showed higher removal of NH_3^-N and Mn compared to HF-SSF. In contrast, HF-SSF exhibited higher removal of NO_3^-N, Fe and PO_4^{3-}. Both VF-SSF and HF-SSF could achieve up to 95 % removal of nutrients and more than 80 % of heavy metals presence in leachate.

KEYWORDS: Leachate treatment, constructed-wetlands, vertical flow, horizontal flow.

Introduction

Leachate is generated as water percolates through solid waste deposited in landfill and become contaminated once in contact with the decomposing waste (Wilson, 1981). It contains high content of toxic compounds including iron, chlorides, organic nitrogen, phosphate and sulphate. Besides, it is also high in organic matters and inorganic ion concentrations which may contribute to the pollution of environment (Kjeldsen et al., 2002). Surface water and ground water pollutions are two forms of environmental problems as a result of water resources contamination by leachate spills.

Constructed wetland is an alternative approach to treat leachate. The operation of this system is a replication to the biological and chemical removal processes of contaminant by natural wetlands. Reduction in biological oxygen demand (BOD), total suspended solid (TSS), total nitrogen (TN), phosphorus (P) and pathogen is achieved by flowing the wastewater through this vegetated subsurface constructed wetland system. Metals compounds are the pollutants that are most likely to accumulate in wetlands receiving wastewater. The probabilities of process in order to remove metals from leachate are bioaccumulation, biotransformation and biodegradation that can occur simultaneously in the constructed wetland systems (Kadlec and Knight, 1996). Previous studies have demonstrated the successful implementation of this approach in treating various composition of leachate (Robinson, 1990, Staubitz et al., 1989; Surface et al., 1993). In fact, constructed-wetland technology for leachate treatment has been applied widely in the United Kingdom and United States of America. In the UK, reed beds are used to treat leachate from landfills (Robinson, 1990). Meanwhile, SSF constructed wetlands have been utilised since 1989 in Ithaca, New York (Staubitz et al., 1989; Surface et al., 1993).

Two types of constructed wetland systems were designed and considered in this paper. The systems are vertical subsurface-flow (VF-SSF) and horizontal subsurface-flow (HF-SSF) constructed wetlands. Both systems were vegetated with emergent plant (*L. flava*) which acts as the natural filters. The performance of VF-SSF and HF-SSF systems was evaluated by comparing efficiency of those systems in removing nutrients and heavy metals. Nutrients of concern include ammonia (NH_3^-N), nitrate (NO_3^-N) and orthophosphate (PO_4^{3-}), while heavy metals of concern are Ferum (Fe) and Manganese (Mn).

Materials and Methods

Leachate

Raw leachate samples used in this study were collected from Tanjung Langsat landfill, Johor, Malaysia. The composition of NH_3^-N, NO_3^-N, PO_4^{3-}, Fe and Mn in raw leachate was determined using HACH DR 4000 spectrophotometer. The selection of the spectrophotometer has been made as it has been used extensively in analysis of nutrients and heavy metals in various wastewater treatments study (Joseph et al., 2004 and Ni'am et al., 2007).

Media

The media used in this study consists of a layer of coarse stone with 15-20 mm diameter with thickness of 2 cm, followed by a layer of fine stone 5-10 mm diameter with thickness of 1 cm, a mixture of sand and soil with ratio 1:3, with thickness of 5 cm and a layer of soil at the surface with thickness of 2 cm.

Plant

Capacity in accumulating and removing heavy metals are varied according to plant species. Types of plants found in subsurface-flow wetlands that commonly used in numerous research such as *Phalaris arundincea* (reed canarygrass), *Typha.* (cattails), *Scirpus.* (bullrushes) and *Glyceria maxima* (sweet mannagrass). Those are aquatic plant that usually found in polluted water bodies and have been suggested for wastewater treatment as they have the ability to accumulate pollutants, without giving an impact on their growth and development. *Limnocharis flava* (yellow burhead) is one of the most common wetland plants available in this region as it is also one of the wetland plants in Putrajaya wetland (Lim et al, 1998). The scarcity of data on the effectiveness of *Limnocharis flava* (yellow burhead) has prompted us to undertake this research.

Experimental Design of Subsurface-Flow Constructed Wetlands

Two subsurface-flow constructed wetlands labeled as VF-SSF and HF-SSF were built separately. A complete constructed wetland system assembled comprised of a storage tank with the volume capacity of 50 L, two plastic valves to control the flow rate of leachate and a trapezoidal tank with the dimension of 0.38 m length, 0.28 m width and 0.30 m depth and a settling tank. The storage tank was used to store bulk leachate. Meanwhile, the trapezoidal tank contained a bed of layered stone and soil media through which the leachate would flow. Eight clusters of *L.flava* were also planted at the surface of the trapezoidal tank and performed as the artificial wetland. The schematic diagram of SSF constructed wetlands design used in the experiment is presented in **Figure 1**. The third system without any vegetation was built as control.

The operation of VF-SSF and HF-SSF is differentiated by the flow regime of leachate in the bed of wetland tank (Tank C and D). In VF-SSF, the untreated leachate entered at the bottom side of the Tank C and vertically flowed out through an exit channel located at the upper part of the tank. On the other hand, the untreated leachate entered Tank D in the HF-VSS from the upper channel and horizontally flowed towards the exit channel at the bottom of the tank. **Figure 2** illustrates the direction of untreated leachate flow within VF-SSF and HF-SSF system respectively.

In each treatment cycle, the untreated leachate from storage tank was gravitationally loaded to the wetland tank (Tank B, C or D) at a constant rate of 15 ml/min and retained in the wetland tank to achieve approximately 5 hours/cycle of hydraulic retention time (HRT). The leachate left the wetland tank as leachate effluent and collected in the settling tank. At the end of every respective cycle, the partially treated leachate collected in the settling tank was recirculated to the storage tank before proceed to the next treatment cycle. VF-SSF, HF-SSF and control systems were concurrently operated according to that similar cycle procedure and prolonged for 18 days continuously. The influent and effluent samples were taken three times per week from each system and analysed.

Determination of Nutrients and Heavy Metal Contents in Influent and Effluents Samples

Influent and effluent samples taken from SSF constructed wetland systems were analysed to determine the content of nutrients (NH_3^-N, NO_3^-N, PO_4^{3-}), and heavy metals (Fe and Mn).

Performance Evaluation of SSF Constructed Wetlands

The efficiency of VF-SSF and HF-SSF constructed wetlands in removing nutrients and heavy metals were evaluated by comparing the rate of removal for both systems using plug-flow first order model expressed in Equation 1.

$$C_i / C_0 = e^{-kt} \qquad (1)$$

Where C_i is effluent pollutant concentration in mg/L, C_0 is influent concentration in mg/L, k is the first-order removal rate constant, day^{-1}, t is nominal hydraulic retention time in day. Pollutant removal rate ($g/m^2.day$) is defined as the hydraulic loading rate multiply by the difference in concentration between the influent and effluent. Analysis of variance (ANOVA) was employed to reveal significant differences for all treatment systems. Statistical significance differences were tested at $p \leq 0.05$ (95% levels of significance).

Results and Discussion

Raw leachate sample have been treated by circulating the leachate through control, VF-SSF and HF-SSF constructed wetland systems. The effluent discharged after 18 days of operation was analysed in order to determine the concentration of nutrients and heavy metals. The efficiency of respective SSF constructed wetland system was compared in terms of percent removal and rate of removal for nutrients and heavy metals.

Nutrients and Heavy Metals Removal

Table 1 summarises the nutrient removal efficiency of control, VF-SSF and HF-SSF constructed wetland system. The results highlighted in **Table 1** indicated that both VF-SSF and HF-SSF systems were capable of removing higher degree of nutrients presence in landfill leachate compared to control system. It is suggested that the presence of vegetations, *L.flava* improved the treatment efficiencies of NH_3^-N and NO_3^-N. *L.flava* possibly assimilated NH_4^-N into its plant tissue and provided suitable environment for nitrification-denitrification in the root zone known as rhizosphere. Similar observation was also demonstrated in constructed wetland system developed using other effective vegetations (Brix, 1994 and Hammer et al., 1993). As suggested in Galbrand (2003), the NH4-N would be oxidised to nitrite (NO_2^-) by nitrosomonas and eventually oxidised to nitrate (NO_3^-) by nitrobacter bacteria. Marginal improvement in terms of PO_4^{3-} removal was observed in VF-SSF and HF-SSF systems compared to that of Control system. This finding suggested that the *L.flava* was ineffective in removing PO_4^{3-} from leachate. The removal range of 52.8 – 61.9 % achieved in three systems is probably attributed to accumulation of PO_4^{3-} in media substrates. Soil substrates of wetland have been identified as the ultimate sinks for PO_4^{3-}. Low solubility PO_4^{3-} could easily bind to soil surface through chains of precipitation and adsorption reactions causing a reduction in PO_4^{3-} concentration in effluent flow. This result was consistent with (Rosolen, 2000; Kim and Geary, 2000; Davis et al., 1993; Reed et al., 1995 and Vymazal, 2005).

Table 2 shows the heavy metal treatment performance of control, VF-SSF and HF-SSF constructed wetland systems. All systems performed more than 90 % removal of Fe. However, the percentage differences of less than 5% between control and vegetated SSF constructed wetland systems suggesting that the removal of Fe has been governed by chemical precipitation and sorption on the sediment of wetland. A slight improvement observed in vegetated SSF system designated that macrophytes like *L.flava* facilitated the removal of Fe through soil substrates of wetland. This is in agreement with Reed et al., (1995) and Lim, (2002). Greater removal results exhibited in VF-SSF and HF-SSF systems compared to that of control system indicating the significant role of *L.flava* in reducing the concentration of heavy metals, namely Fe and Mn from leachate. In agreement with Kadlec and Knight (1996), emergent vegetations reduce the concentration of heavy metals from wastewater by retaining them in the root or foliar surface. As supported in Sawidis et al., (2001), the heavy metal uptake and removal capacities may vary with plant species.

The findings of this study proposed that the removal of nutrients and heavy metals could occur through soil substrates of wetland and/or perform by *L.flava* bed planted at the surface of wetland. Significant improvement in removal efficiency of NH_3^-N, NO_3^-N, Fe and Mn achieved by using VF-SSF and HF-SSF constructed wetland systems signifies the major contribution of *L.flava* plant in enhancing the overall performance of SSF constructed wetland system. Therefore, *L.flava* plant is worth to be considered as an emergent, hydrophytic plant for better landfill leachate treatment.

Comparison of Removal Performance in VF-SSF and HF-SSF Constructed Wetland Systems

Figure 3 to 5 depicted the graphical representation of plug flow first order model for removal of nutrients using control, VF-SSF and HF-SSF constructed wetland systems. The k values which represent the removal rate constant were determined from the plot and summarised in **Table 3**. The k value implies the rate of nutrient or heavy metal removal in the SSF constructed wetlands. The higher the k value, the faster the nutrient or heavy metal could be removed from the system.

Based on **Table 3**, the k value for NH3-N removal using VF-SSF system was higher than that of HF-SSF system. This result suggests that the NH_3^-N removal process in VF-SSF constructed wetland system is more rapid than that of HF-SSF system. Acceleration of NH_3^-N removal might be attributed to the higher oxygen capacity in the VF-SSF system. Oxygen is required for oxidising NH_3^-N to nitrite (NO_2^-) through nitrification-denitrification process. Oxygen can retain in the system in the form of dissolved oxygen (DO). Vertical flow of influent wastewater improves the DO content in the wetland. This is supported in Vymazal (2005) and Tanner (1994) whereby a VF wetland could receive approximately 2.5 times greater DO within the influent wastewater than the HF. Apart from that, diffused of oxygen from the atmosphere through the water surface could occur via plant shoots into the root zone.

In contrast, HF-SSF shows higher k values compared to VF-SSF in the case of NO_3^-N and PO_4^{3-} removal process. The higher removal rate of NO_3^-N indicated that the shallow bed media and flow regime of HF-SSF constructed wetland had provided better atmosphere for inducing denitrification of NO_3^-N to nitrogen gas (N_2) by anaerobic bacteria. In line with Garcia et al., (2004), the result indicated that the shallower beds (<0.4 m in depth) and HF flow regime were enhanced oxygen diffusion at the air-water interface thus induced the denitrification process. The higher removal rate of PO_4^{3-} in HF-SSF constructed wetland system on the other hand revealed that this system was capable of reducing the concentration of PO_4^{3-} under low DO concentration. A similar observation has been reported in Holford and Patrick, (1979). Reddy and D'Angelo, (1997) and Nurnberg et al., (1987). Low oxygen capacity in HF wetland leads to lower DO concentration in the HF-SSF constructed wetland system. This condition promotes anaerobic activity which eventually provides very conducive environment for digestion of PO_4^{3-}. In addition, retention of PO_4^{3-} in *L.flava* plants could also contribute to the reduction of PO_4^{3-} concentration in leachate effluent. Wetland plants are capable to adapt with low DO conditions by secreting oxygen from their roots. This phenomenon indirectly encourages the formation of aerobic region around the root and allow for PO_4^{3-} retention (Drizo et al., 1997).

Figure 6 to 7 show the graphical representation of plug flow first order model for removal of Fe and Mn respectively using control, VF-SSF and HF-SSF constructed wetland systems. The k values which represent the removal rate constant for both heavy metal elements were determined from the plot and listed in **Table 4**. **Figure 6 and 7** revealed that the concentration of Fe and Mn decreased over time of treatment for all SSF constructed wetland systems. This similar trend has been observed in the removal process of nutrients showing that the heavy metal removal efficiency of SSF systems also improved over time of treatment operation. k values given in **Table 4** on the other hand show that the removal rate of Fe and Mn are different in these three systems. Fe removal occurred at greater rate in HF-SSF constructed wetland system that that of VF-SSF system. This is because the k value for HF-SSF is much larger than the k value for VF-SSF system. In contrast, VF-SSF system performed more efficient removal of Mn since the rate of Mn removal for this system is larger than that of HF-SSF system. It has been envisioned that the removal of Fe in SSF constructed wetland are likely to take place on the sediment of wetland itself. Therefore, the flow regime applied in HF wetland aided with *L.flava* plants probably was more helpful in inducing the chemical precipitation and sorption of Fe element on the sediment compared to vertical flow regime used in VF wetland as supported in Reed et al., (1995); Lim, (2002) and Ain Nihla, (2008). Higher oxygen capacity in VF wetland can provide aerobic habitat through transferring oxygen from stems to the roots and released it into the rhizosphere. This condition can alleviate the oxygen competition between organic degradation, nitrification, chemical iron oxidation and biological manganese oxidation thus can give some advantages to VF-SSF system over HF-SSF system particularly in removing Mn. High DO concentration enhanced oxidation of Mn mainly through plants and microorganisms activity, thus allowing rapid removal of this element from leachate. Otherwise, versatile metabolism of manganese oxidising bacteria may enable the manganese oxidation under microaerobic conditions (Emerson et al., 1999 and Kappler and Straub, 2005). Analysis of variance (ANOVA) has been used to reveal significant differences for all types of treatment systems. Statistical significance differences were tested at $p \leq 0.05$ (95% levels of significance). **Table 5** shows the p value when comparing significant differences between control, VF-SSF and HF-SSF constructed wetland systems. The ANOVA shows significant differences between control, VF-SSF and HF-SSF constructed wetland systems.

Conclusion

Emergent plant *L.flava* has significant influence in enhancing the overall performance of SSF constructed wetland in treating or removing nutrients and heavy metal. The presence of *L.flava* vegetation improved the overall performance of both VF-SSF and HF-SSF constructed wetland particularly involving the removal of NH_3^-N, NO_3^-N and Mn compared to unplanted SSF constructed wetland. The macrophyte such as *L.flava* plays an important role in constructed wetlands by providing microbial attachments, trapping and settlement of suspended components. Comparison of treatment performance using VF-SSF and HF-SSF constructed wetland systems demonstrated that the flow regime applied within the bed of wetland has some significant effects towards the rate of nutrient and heavy metal removal. Vertical flow applied in VF-SSF system promoted oxygen transfer into wetland and encouraged oxidation of NH_3^-N and Mn. Horizontal flow applied in HF-SSF system supported anaerobic activity for denitrification of NO_3^-N to nitrogen gas (N_2) and digestion of PO_4^{3-} and Fe onto soil sediment in low DO conditions.

References

Abhilash, P.C., Pandey, V.C., Srivastava, P., Rakesh, P.S., Chandran, S. and Nandita Singh, A.P. Thomas. (2009). Phytofiltration of cadmium from water by *Limnocharis flava* (L.) Buchenau grown in free-floating culture system. *Journal of Hazardous Materials.* doi:10.1016/j.jhazmat.2009.05.035.

Ain Nihla, K., Johan, S., Norazian, M.N., Naimah, I., Ayu Wazira, A. (2008). Utilizing a combination subsurface flow and free water surface constructed wetland for landfill leachate treatment. In: Proceeding International Conference on Environmental Research and Technology (ICERT 2008). 28th-30th May 2008. Parkroyal Hotel, Penang. Universiti Sains Malaysia. 996-1000 pp.

Brix, H. (1994). Use of constructed wetlands in water pollution control: historical development, present status, and future perspectives. *Water Science Technology*. 30(11), 209-223.

Davis, T., Cottingham, P. (1993). *Phosphorus removal from wastewater in a constructed wetland.* In: Moshiri, G.A. ed. *Constructed wetland for water quality improvement.* Boca Raton, Fluorida: Lewis Publishers. 315-320 pp.

Drizo, A., Frost, C., Smith, K., Grace, J. (1997). Phosphate and ammonium removal by constructed wetlands with horizontal subsurface flow using shale at a substrate. *Water Science Technology.* 35(5), 95-102.

Emerson, D., Weiss, J.V. and Megonigal, J.P. (1999). Iron-Oxidizing Bacteria are Associated with Ferric Hydroxide Precipitates (Fe-Plaque) on the Roots of Wetland Plants. *Applied Environmental Microbiology*. 65, 2758-2761.

Galbrand, C. (2003). Naturalized treatment wetlands for contaminant removal: A case study of the Burnside Engineered Wetland for treatment of landfill leachate. Msc thesis. Dalhousie University, Halifax, Nova Scotia.

Garcıa, J., Aguirre, P., Mujeriego, R., Huang, Y., Ortiz, L., Bayona, J., (2004). Initial Contaminant Removal Performance Factors in Horizontal Flow Reed Beds Used for Treating Urban Wastewater.*Water Research.* 38, 1669–1678.

Hammer, D., Pullin, B., McCaskey, T., Eason, J., Payne, V. (1993). *Treating livestock wastewaters with constructed wetlands. In: Constructed wetlands for water quality improvement.* Moshiri, G.A. (ed) CRC Press LCC, Boca Raton. 343-348 pp.

Holford, I., Patrick Jr, W. (1979). Effect of Reduction and pH Changes on Phosphate Sorption and Mobility in Acid Soil. *Soil Science Society of America Journal.* 43, 292-296.

Joseph, K., Frank, K., Lena, G., and Gunnel, D. (2004). A Comparative Study of Cyperus papyrus and Miscanthidiumviolaceum-based Constructed Wetlands for Wastewater Treatment in a Tropical Climate. *Water Research.* 38, 475-485.

Kadlec, R. H. and Knight, R. L. (1996). *Treatment wetlands.* CRC Press/LewisPublishers, Boca Raton, Florida. 893 pp.

Kappler, A. and Straub, K.L. (2005). Geomicrobiological Cycling of Iron, Rev. Mineral. *Geochem.* 59, 85–108.

Kim, S. and Geary, P. (2000). The impact of biomass harvesting on phosphorus uptake by wetland plants. In: Proceedings of the 7th International Conference on Wetland Systems for Water Pollution Control. November 11-16. Lake Buena Vista, Florida: International Water Association, 105-112 pp.

Kjeldsen, P., Barlaz, M.A., Rooker, A.P., Baun, A., Ledin, A., Christensen, T.H. (2002). Present a long term composition of MSW landfill leachate: A review. Crit. Rev. *Environmental Science Technology.* 32, 297-336.

Lim, P.E. (2002). Constructed wetland: mechanism of treatment processes and design models. In: Mashhor, M., Lim, P.E., Shutes, R.B. Constructed wetlands: Design, management and education. Universiti Sains Malaysia Publisher: Malaysia.

Ni'am., M.F., Othman, F., Sohaili, J. and Fauzia, Z. (2007). Electrocoagulation Technique in Enhancing COD and Suspended Solids Removal to Improve Wastewater Quality. *Water Science and Technology.* 56 (7), 47-53.

Nurnberg, G., Hartley, K., Davis, E. (1987). Hypolimnetic withdrawal in two north american lakes with anoxic phosphorus release from the sediments. *Water Research.* 21(8), 923-928.

Reed, S., Crites, R., Middlebrooks, E. (1995). *Natural system for waste management and treatment.* 2nd ed. New York: McGraw-Hill, Inc.

Reddy, K. and D'Angelo, E. (1997). Bigeochemical indicators to evaluate pollutant efficiency in constructed wetlands. *Water Science Technology.* 35(5), 1-10.

Robinson, H. (1990). *Leachate treatment to surface water standards using reed bed polishing. In: The use of macrophytes in water pollution control report*, IAWPRC Newsletter, Vol. 3. London: IAWQ. 32 pp.

Rosolen, S. (2000). An evaluation of adsorptive media for improving phosphorus removal in constructed wetlands. Master Thesis. Queen's University, Kingston, Ontario, Canada.

Sawidis, T., Chettri, M., Papaionnou, A., Zachariadis, G., Stratis, J. (2001). A study of metal distribution from lignite fuels using trees as biological monitors. *Ecotoxicology Environmental Safety*. 48, 27-35.

Staubitz, W.W., Surface, J. M., Steenhuis, T. S., Peverly, J. H., Lavine, M. L., Weeks, N. C., Sanford W. E., and. Kopka, R. J. (1989). *Potential use of constructed wetlands to treat landfill leachate. In: Hammer, D. A., Ed. Constructed wetlands for wastewater treatment.* Chelsea: Lewis Publishers. 735-742 pp.

Surface, J.M., Peverly, J.H., Steenhuis, T.S., and Sanford, W.E. (1993). *Effect of season, substrate composition, and plant growth on landfill leachate treatment in constructed wetlands. In Moshiri, G.A., Ed. Constructed wetlands for water quality improvement.* Boca Raton: Lewis Publishers. 461-472 pp.

Tanner, C. (1994). Plants for constructed wetland treatment systems. A comparison of the growth and nutrient uptake of eight emergent. *Ecological Engineering.*7, 59-83.

Vymazal, J. (2005). Constructed wetlands for wastewater treatment. *Ecological Engineering*. 25, 475-477.

Wilson, D.C. (1981). *Waste management; planning, evaluation and technologies.* New York: Oxford University.

Table 1: Nutrient removal efficiency of control, VF-SSF and HF-SSF constructed wetland systems.

Nutrients	Concentration in raw leachate (mg/L)	Removal efficiency (%)		
		Control	VF-SSF	HF-SSF
NH_3^-N	136.0	79.0	94.1	80.4
NO_3^-N	26.5	66.4	69.8	81.9
PO_4^{3-}	52.8	52.3	55.5	61.9

Table 2: Heavy metal removal efficiency of control, VF-SSF and HF-SSF constructed wetland systems.

Heavy metals	Concentration in raw leachate (mg/L)	Removal efficiency (%)		
		Control	VF-SSF	HF-SSF
Fe	0.81	92.6	95.0	96.3
Mn	0.40	77.5	87.5	82.5

Table 3: Nutrient removal rate constant (k values) of Control, VF-SSF and HF-SSF constructed wetland systems.

Nutrients	k values (day^{-1})		
	Control	**VF-SSF**	**HF-SSF**
NH_3^-N	0.331 day^{-1}	0.445 day^{-1}	0.379 day^{-1}
NO_3^-N	0.246 day^{-1}	0.310 day^{-1}	0.346 day^{-1}
PO_4^{3-}	0.118 day^{-1}	0.158 day^{-1}	0.193 day^{-1}

Table 4: Heavy metal removal rate constant (k values) of Control, VF-SSF and HF-SSF constructed wetland systems.

Heavy metals	k values (day^{-1})		
	Control	**VF-SSF**	**HF-SSF**
Fe	0.485 day^{-1}	0.599 day^{-1}	0.730 day^{-1}
Mn	0.125 day^{-1}	0.368 day^{-1}	0.239 day^{-1}

Table 5: Statistical Analysis of ANOVA between Control, VF-SSF and HF-SSF constructed wetland systems.

Parameters	95 % levels of significance p value (Significant $p \leq 0.05$
NH_3^-N	1.227E-06
NO_3^-N	5.525E-08
PO_4^{3-}	2.299E-10
Fe	1.678E-13
Mn	4.532E-07

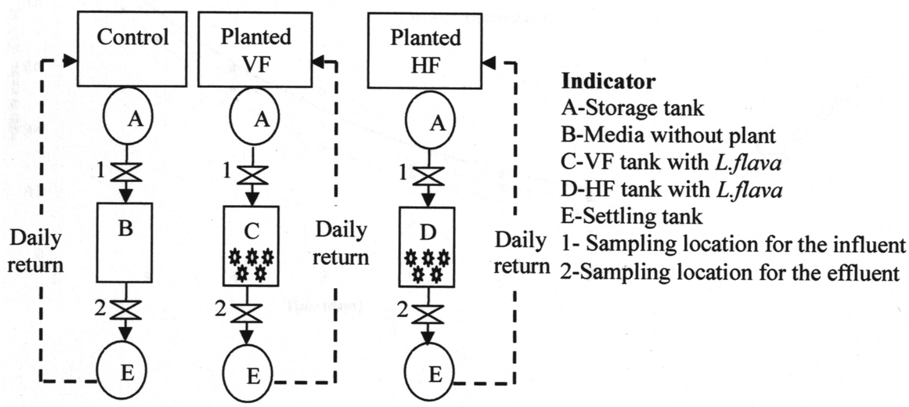

Figure 1: Schematic diagram of; (a) control, (b) VF-SSF and (c) HF-SSF constructed wetland system design.

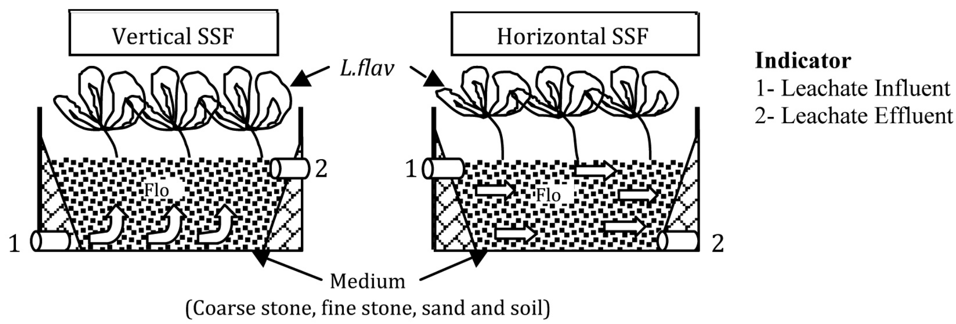

Figure 2: Cross section of (a) vertical subsurface flow (VF-SSF), and (b) horizontal subsurface flow (HF-SSF) constructed wetland used in the experiment. .

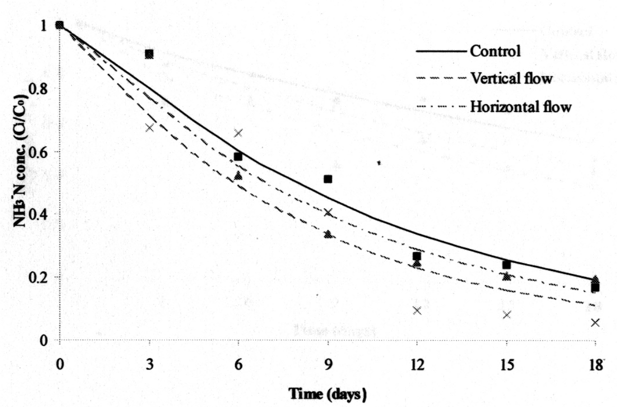

Figure 3: Comparison of NH_3-N concentration (C_i/C_o) in control, vertical flow and horizontal flow constructed wetland systems.

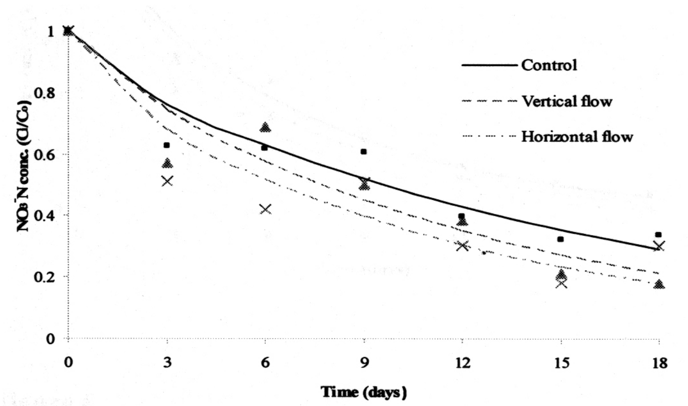

Figure 4: Comparison of NO_3^-N concentration (C_i/C_o) in control, vertical flow and horizontal flow constructed wetland systems.

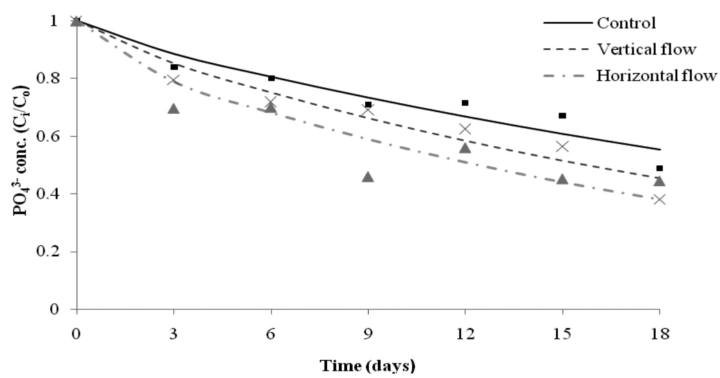

Figure 5: Comparison of PO_4^{3-} concentration (C_i/C_o) in control, vertical flow and horizontal flow constructed wetland systems.

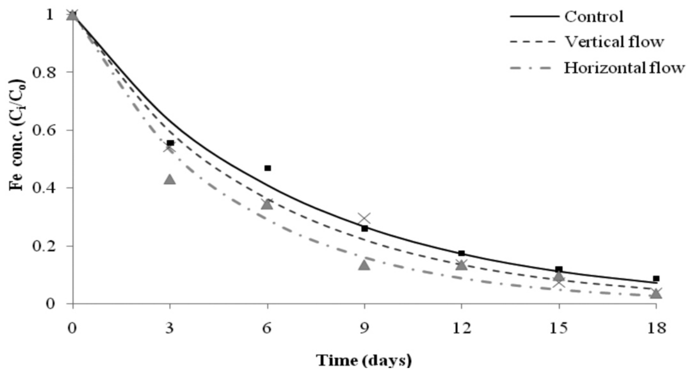

Figure 6: Comparison of Fe concentration (C_i/C_o) in control, vertical flow and horizontal flow constructed wetland systems.

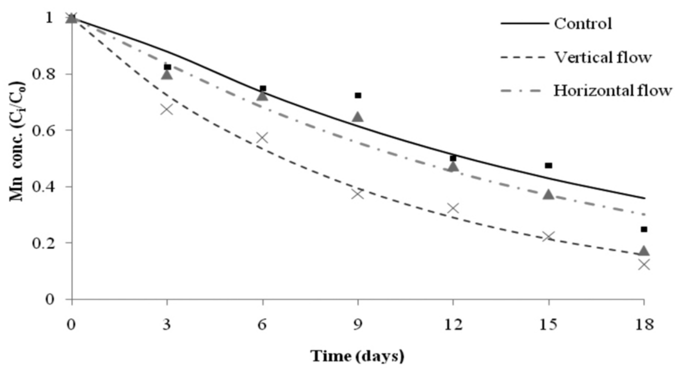

Figure 7: Comparison of Mn concentration (C_i/C_o) in control, vertical flow and horizontal flow constructed wetland systems.