

Performance of tropical vertical subsurface flow constructed wetlands for leachate treatment at different hydraulic loading rates

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Abstract

This study is focused on the investigation of three different types of plant species namely; Narrow leaf Cattail (*Typha angustifolia*), Green Bulrush (*Scirpus atrovirens*) and Umbrella Palm (*Cyperus alternifolius*) for treatment of leachate. Twelve laboratory scale subsurface flow constructed wetland models were operated in batch mode. Four models, each containing similar plant species were fed with synthetic leachate having four different concentrations (25%, 50%, 75% and 100%) and 7 days HRT was given. The duration of a batch run was 12 weeks. Removal efficiencies of BOD₅, COD, PO₄³⁻, TC, and TN were measured. Evapotranspiration (ET) loss of each test run was also assessed. According to the results, the constructed wetland planted with Umbrella palm and fed with 25% leachate showed the best pollutant removal efficiencies of 99.26% for BOD₅, 99.61% for COD, 98.78% for TN and 97.34% for TC. Highest ET potential of 93.57% was also observed from the constructed wetland with umbrella palm fed with 25% leachate. Two way ANOVA analysis was carried out for each plant species and leachate concentration and the Umbrella Palm species was identified as the best for leachate treatment.

Key words:

Constructed wetlands, landfill leachate, plant species, pollutant removal

1. Introduction

Solid waste disposed in landfills are stabilized by combination of physical, chemical and microbial processes. As a result of landfill degradation, a liquid known as leachate is formed (Tyrrrel et al., 2002). Landfill leachate is a highly complex wastewater. Due to anaerobic conditions and long retention times prevailing in landfills, the landfill leachate usually contains high concentrations of nutrients, organic compounds and heavy metals which, if not properly collected and treated, can cause serious pollution by contaminating surface and groundwater sources (Dorota and Ewa, 2008; Christansen et al., 1994). Although several physical, chemical and biological treatment processes can be employed to minimize adverse environmental impacts of landfill leachate, they can be expensive in the construction, operation and may also require high-skilled laborers for operation (Sawaittayothin and Polprasert, 2007).

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Constructed wetlands (CWs) are engineered systems which simulate the same processes that occur in natural wetlands, within a more controlled environment (Kadlec and Knight, 1996). CWs have reasonably a small ecological footprint, which has been designed and implemented in accordance with the natural processes involving wetland vegetation, soils, and the associated microbial assemblages to assist in treating wastewaters. These systems have been effective in treating various types of wastewaters, due to its support for diverse population of microbial communities and it offers quiescent conditions for sedimentation, adsorption, filtration, and ion exchange (Cothren et al., 2002; Verhoeven et al., 2006).

Since CW systems could potentially tolerate variable volumes of water and varying contaminant levels, it is highly applicable for treating landfill leachate (Akinbileet et al., 2012). Several studies have been conducted on the factors that can affect contaminant removal in CWs treating landfill leachate (Yalcuket et al., (2009). Lavrova et al., (2011) studied the effect of the flow direction on the treatment efficiency in the CWs. Kietlińska and Renman (2005) reported that recirculation of treated effluent positively affects the substrate media. The variation of the performance with the type of pre-treatment was reported by Wojciechowska et al., (2010). Although majority of previous studies had used domestic or municipal wastewater to investigate the role of the plant species in CWs (Allen et al., 2002), studies done on industrial wastewaters for example paper-mills (Abira et al., 2003), tannery (Calheiros, et al., 2007), and fish-farm (Naylor et al., 2003) and ground water (Lin et al., 2002) are also available. The effect of loading rates was the most common factor evaluated along with plant species (Brisson and Chazarenc, 2008). Two or more loading rates were either evaluated simultaneously with plant species in a factorial experimental design (with or without replicates) or by modifying loading rates over time in the same units and comparing the different time series.

It is commonly accepted that macrophytes play an essential role in CWs. Brix (1997) and Stottmeister et al., (2003) reported that macrophytes provide a large surface area for an attached microbial growth and supply reduced carbon and oxygen in the rhizosphere. The reduced flow velocity by macrophytes stabilized the surface of the bed and insulated the surface against frost in the winter. Previous studies indicated that the type of the plant is often considered minor in subsurface flow CWs for pollutant removal (Mander et al., 2003), while some other studies revealed that the growth characteristics of different plant species may affect the potential for uptake and transformation of nutrient and heavy metals (Tanner, et al., 1996; Maltais-Landry et al., 2009). Benefits of macrophytes have been repeatedly demonstrated, but, it remains unclear whether significant differences exist in the removal efficiencies among plant species of comparable life forms and sizes (Brisson and Chazarenc, 2008).

Even though several CW studies with plant species are reported in the literature, there has been a dearth of information on the assessment of plant species on the removal efficiency of contaminants from landfill leachate. Therefore, the primary objective of this study is to i) evaluate the effect of plant species towards the CW performance when treating landfill leachate; and ii) to find the most appropriate leachate concentration to be introduced to a constructed wetland system.

2. Materials and Methodology

2.1 Plant Species

Three plant species namely narrow leaf Cattail (*Typha angustifolia*), green Bulrush (*Scirpus atrovirens*) and Umbrella Palm (*Cyperus alternifolius*), were selected for this study.

2.2 Experimental set up

Twelve (12) identical lab scale subsurface flow constructed wetland (SSF CW) models were constructed using plastic vessels each with dimensions of 25cm×20 cm×34 cm (length × width × depth). A sampling point (faucet) was fixed at 3 cm from the bottom of each CW model for the collection of treated effluents. The faucet inlet was covered with a plastic net to prevent debris from clogging the sampling point.

Gravel, sand and silt were used as the substrate media in each CW. A 15 cm gravel layer, 10 cm sand layer and a 5 cm loam soil layer were placed from bottom to top to facilitate favorable conditions for plant growth. A plastic net was placed between soil and gravel layers to minimize disturbances to the silt layer.

One plant species was planted in 4 CWs so that 12 models were planted with 3 species of plants. Plant density in each model was maintained at 3 shoots per CW.

2.3 Synthetic leachate

Stock solution of synthetic leachate was prepared according to the formula presented by Jamie et al.,(2004). The concentration of synthetic leachate is given in Table 2.1.

Table 2.1: Synthetic leachate composition

Common chemical	Unit: g per liter
Sugar	1000 g
CH ₃ COONa	100 g
K ₂ HPO ₄	2.22 g
NaHCO ₃	35.72 g
K ₂ CO ₃	35.37 g
NaCl	9.96 g
CaCl ₂	15.96 g
MgCl ₂ .6H ₂ O	15.89 g
MgSO ₄ . 7H ₂ O	8.04 g
CO(NH ₂) ₂	1000,g
<i>Trace heavy metal</i>	Unit: mg per liter
FeSO ₄	200
H ₃ BO ₄	5
ZnSO ₄ .7H ₂ O	5
CuSO ₄ .5H ₂ O	4
MnSO ₄ .7H ₂ O	50
(NH ₄) ₆ Mo ₇ O ₂₄ .4H ₂ O	5
Al(SO ₄) ₃ .16H ₂ O	3
CoSO ₄ .7H ₂ O	15
NiSO ₄ .6H ₂ O	50
96% conc. H ₂ SO ₄ (AnalR)	1 ml

Four different feed solutions (25%, 50%, 75% and 100% of stock concentrations) were prepared by diluting the stock solution with normal tap water.

2.4 Leachate loading

Initially all 12 CW models were fed with tap water and allowed for plant shoots to stabilize (to develop couple of leaves). Once stabilized, the first CW model was fed with 5 L of 25% leachate using a watering can, manually. The second CW model with the same plant species was fed with 50% leachate solution, the third one with 75 % and the last one with 100% solutions. This procedure was repeated for all 3 types of plants species.

CW models were operated in batch mode with a hydraulic retention time (HRT) of 7 days. After keeping intact for 7 days, leachate was drained through the sampling faucet. The leachate volume remaining after 7 days of batch operation was also measured. Water quality was tested for 5-day biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), total nitrogen (TN), phosphate concentration (PO₄³⁻) and total carbon concentration (TC).

The above procedure was repeated for all 12 models for 12 consecutive batches.

2.5 Evapotranspiration (ET) Loss

In CWs, reduction of wastewater volume occurs with time due to both evaporation and transpiration, which is known as the Evapotranspiration (ET) loss. This may have an effect on the treatment efficiency of CWs. The ET loss was estimated as per the equation 2.1.

$$ET \text{ loss} = \frac{(5 - \text{leachate volume in litres remaining after 7 days of retention period})}{5} \times 100 \quad (\text{Equation 2.1})$$

2.6 Statistical analysis

Pollutant removal efficiencies of 5 selected parameters (COD, BOD₅, TN, TC, PO₄³⁻) were estimated according to the equation 2.2,

$$\text{Removal efficiency} = \frac{\text{Initial concentration} - \text{Final concentration}}{\text{initial concentration}} \times 100 \quad (\text{Equation 2.2})$$

Removal efficiencies obtained from 12 CWs for 12 repeated tests were subjected to two way ANOVA analysis. The analysis was conducted using Minitab (16.2.4.0) software. The analysis was conducted to determine significant differences among different systems and comparison of means was done in order to find the most appropriate plant species and best leachate concentration for the optimal removal of contaminants.

3. Results and Discussion

In this study three plant species (Cattail, Bulrush and Umbrella palm) were grown in 12 identical SSF CW sand tested for 4 different leachate concentrations (25%, 50%, 75% and 100% of stock leachate concentration). Tests were conducted in batch mode with a 7 day HRT. Pollutant removal efficiencies of BOD₅, COD, PO₄³⁻, TC, and TN were estimated. Percentage reduction of leachate volume during the 7 day retention period was also assessed.

Since the pollutant levels in natural leachate could vary with the climatic condition, solid waste composition and many other variables; synthetic leachate prepared according to the formula presented by Jamie et al.,(2004) was used for this study. Composition of the stock leachate solution is given in Table 3.1.

Table 3.1: Concentration of synthetic leachate stock solution

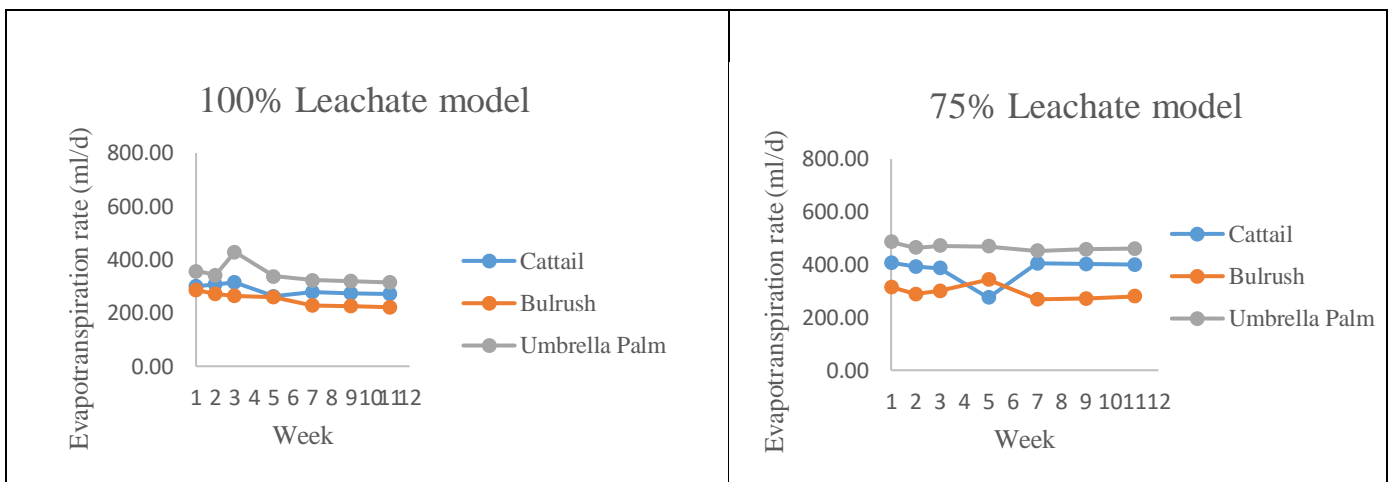
Pollutant Parameter	Value	Detection Method
BOD ₅	442.7	Winkler method
COD	2600	Reactor digestion method
PO ₄ ⁻	4.31	PhosVer 3 (Ascorbic Acid) method
TC	1217.7	TOC analyzer
TN	1039.4	TOC analyzer

After leachate was introduced to constructed wetland systems, moss layers had appeared in the 25% and 50% leachate fed systems within a couple of days. However, after few weeks of operations similar moss layers had appeared in the 75% and 100% leachate systems. This observation indicated that the feed concentrations in 25% and 50% CWs can readily be used by primitive life forms, but higher feed concentration (75% and above) need a comparatively long period for such life forms to proliferate in harsher environmental conditions.

Plants in CWs except cattail with 75% and 100% leachate showed a good tolerance against leachate. After about two months from initiation, cattail shoots in the 100% and 75% systems appeared to be dried and destroyed, but new shoots appeared in the 3rd month. Umbrella palm shoots showed a better tolerance for leachate as the plant growth was not disturbed by the application of leachate.

3.1. Evapotranspiration

A significant ET loss has occurred in all CWs, especially in systems fed with 25% and 50% leachate (Figure 3.1). This may be due to the evaporation which has occurred due to high air temperature and low humidity on top of increased transpiration due to the plant growth. In tropical countries a considerable amount of water evaporates from water bodies especially under warm and windy conditions. Certain percentage (~ 95%) of water absorbed by the plant roots has also escaped from the small pores in leaves (transpiration). The amount of transpiration varies from plant to plant. According to the Białowiec and Wojnowska-Baryla (2007) and Headley et al., (2012) water losses through transpiration is high in Macrophytes as they have inherently low efficiencies of water use. Of the three plant species, the highest ET rate against four different leachate loading was observed in umbrella palm plants (71.95%).



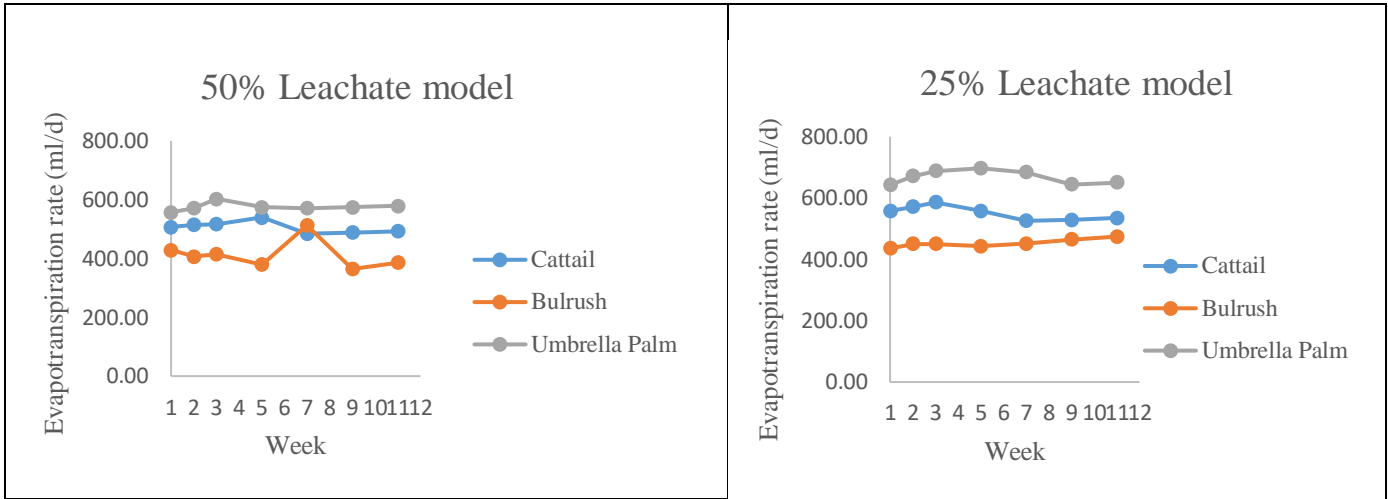


Figure 3.1: Shows different evapotranspiration models

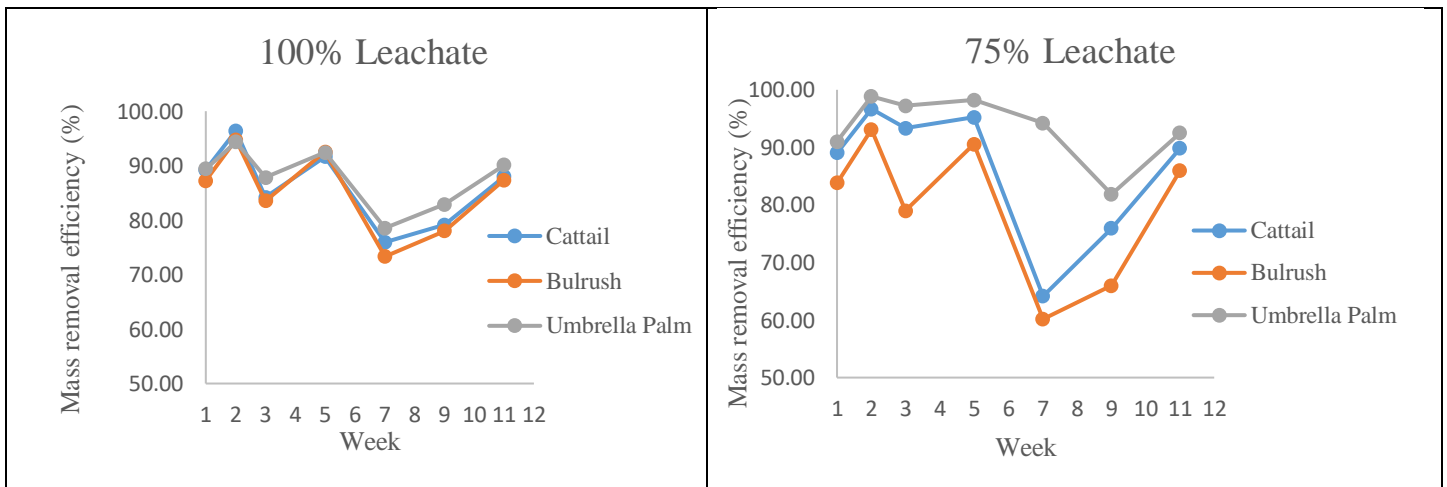
Evapotranspiration losses have significantly changed with the leachate concentration. The mean ET losses for leachate concentrations in 25%, 50%, 75% and 100% CWs were 78.04%, 69.78%, 53.27% and 41.26%, respectively. Results indicated that Umbrella palm containing CWs with 25% leachate concentrations exhibited the highest ET potential.

3.2. Treatment performance

All CW units performed well in the treatment of synthetic leachate, maintaining a high removal efficiency at all tested conditions. This section contains the results of the batch tests for the removal of BOD₅, COD, TN, TC and PO₄³⁻.

3.2.1 BOD₅

Results of statistical analysis indicated that both the plant species and the leachate concentrations have significant impacts ($P < 0.05$) on BOD₅ removal efficiencies. The highest mean BOD₅ removal efficiency was reported by Umbrella palm plants for 25% leachate concentration (Figure 3.2).



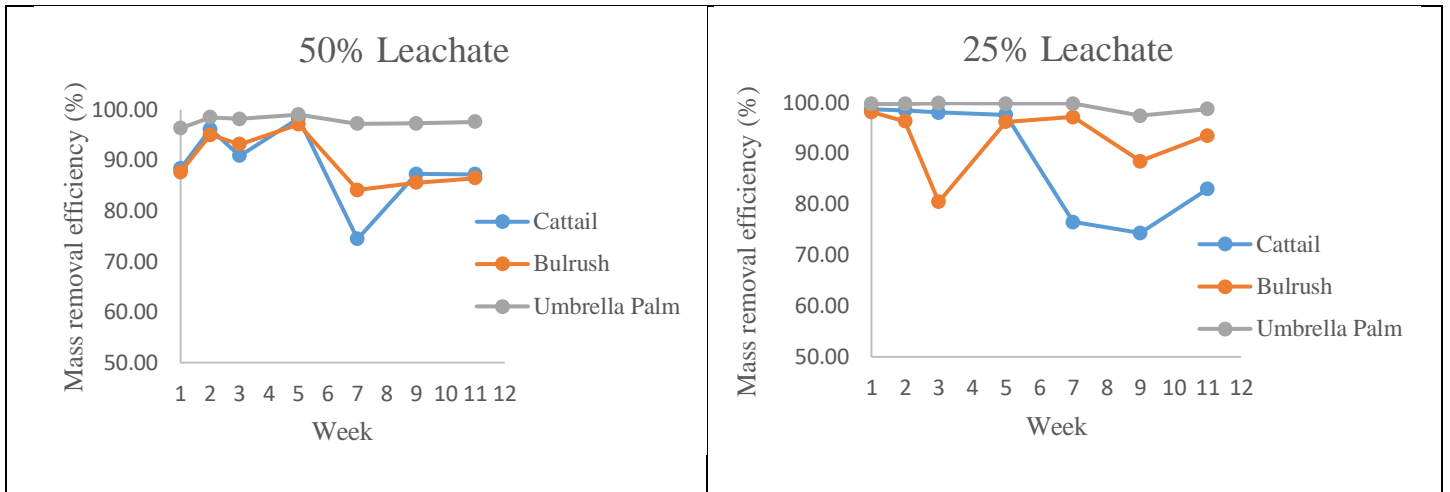


Figure 3.2: BOD removal efficiencies in the presence of different plant species under different leachate loading

3.2.2 COD

All three plant species showed good performance in COD removal with removal efficiencies of above 70% in all testes (Table 3.2). A slight decrease of removal efficiency with time was shown by Cattail and Green bulrush species against 100% leachate. Even though a considerable drop had occurred in the 9th week, umbrella palm exhibited the highest average removal efficiency (89.62±3.62%).

Table 3.2: COD removal efficiencies in the presence of different leachate loading rate.

	100% loading	75% loading	50% loading	25% loading
<i>Typhaangustifolia</i>	83.06±6.16%	88.69±6.96%	96.16±1.99%	99.14±0.95%
<i>Scirpus atrovirens</i>	79.66±5.41%	85.62±5.10%	87.75±3.81%	98.24±2.08%
<i>Cyperus alterufolius</i>	89.62±3.62%	96.52±2.24%	98.73±1.20%	99.61±0.39%

Comparatively higher average COD removal efficiencies were observed in CWs with 50% loading than CW systems with 75% and 100% leachate. In this concentration range also, the highest average removal efficiency was reported by Umbrella Palm.

The highest COD removal efficiencies and lowest variance induced by plant species was observed in CWs with 25% leachate loading. All three plant species performed well at the lowest leachate concentration.

3.2.3 Total Nitrogen (TN)

In the presence of concentrated leachate (100%), the CWs planted with Cattail had shown a significantly high ($p < 0.05$) TN removal. Even though the value had dropped after the first feeding, the removal efficiency still remained at a higher level (73.54±2.45%). Removal efficiency of the system with Green bulrush remained stable at around 70% after the first 5 weeks. The CW with Umbrella palm exhibited the highest average removal efficiency of 76.40±3.99%. Performances of plant species at different leachate concentrations are given in (Figure 3.3).

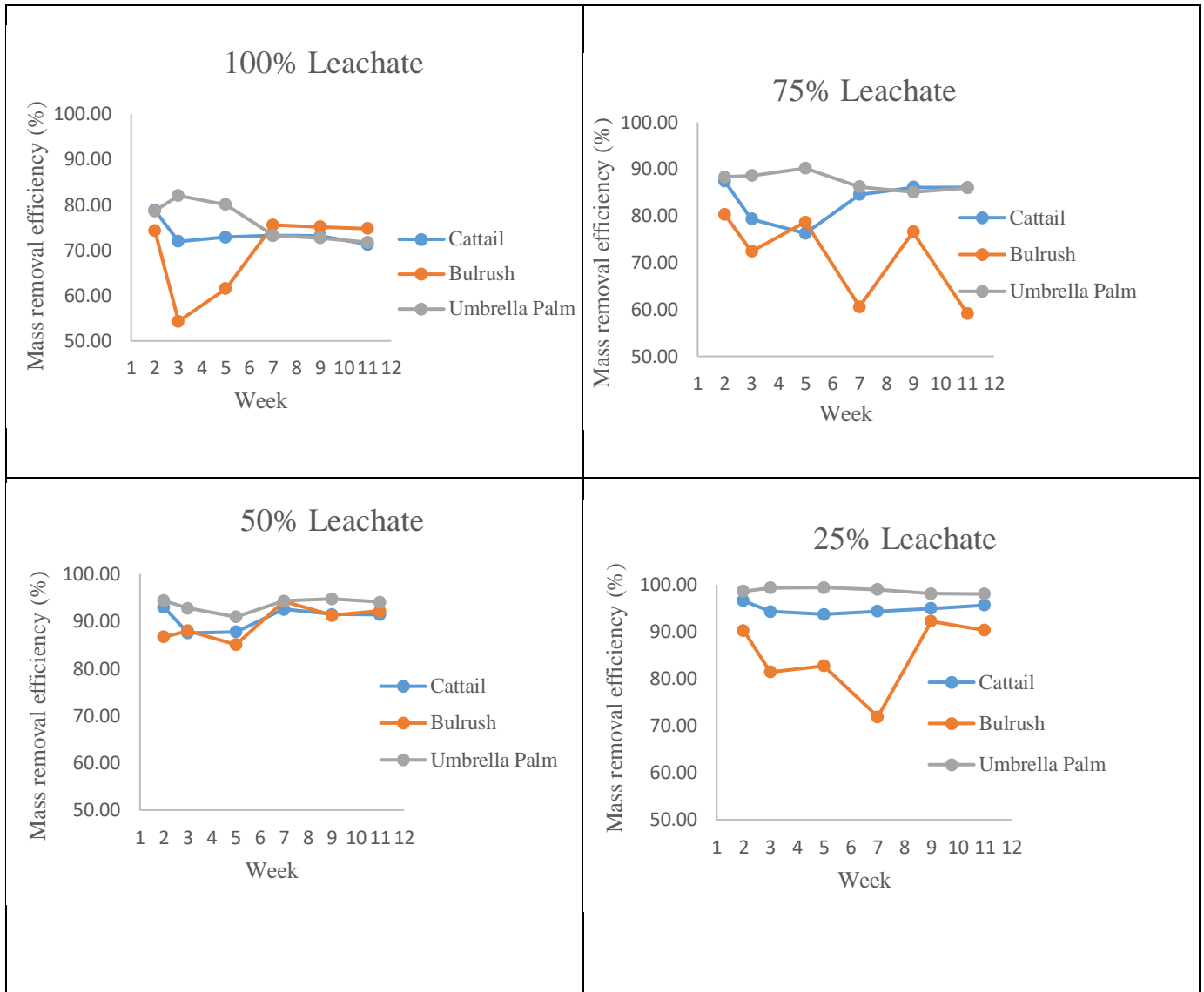


Figure 3.3: TN removal efficiencies in the presence of different plant species under different leachate loading

For both Cattail and Green bulrush, the TN removal efficiencies exhibited almost constant values, regardless of the leachate loading. The CW with Umbrella palm showed the highest average TN removal efficiency among the 12 tested twelve models, regardless of leachate loading. The highest removal efficiency was observed in CWs at 25% leachate loading (97.34%).

The plant species and the loading strength of leachate showed a significant ($P < 0.05$) impact on TN removal. The interaction between TN removal, plant species and loading strength was also significant ($P < 0.05$).

3.2.4 Total Carbon (TC)

In CWs, the organic carbon is converted to CO_2 or CH_4 by microbial degradation and is absorbed by plants for cell synthesis. Carbon removal is a major function of CWs. Therefore TC removal efficiency by different plant species was also studied.

Slight decrease of TC removal efficiency with time was observed in all treatment systems which is attributed to initial adsorption by the materials in CWs. Models planted with Green

bulrush showed the poorest TC removal efficiencies ranging from 67.97% to 82.83%. The highest removal efficiencies (88.72-97.34%) were exhibited by CW splanted with Umbrella palm. The CW planted with Umbrella palm and fed with 25% leachate showed the highest average TC removal efficiency at 97.34±1.40%.

The P-value of less than 0.05, indicates that significant differences exist in TC removal efficiencies in the CWs with different plant species and different leachate loadings (Figure 3.4).

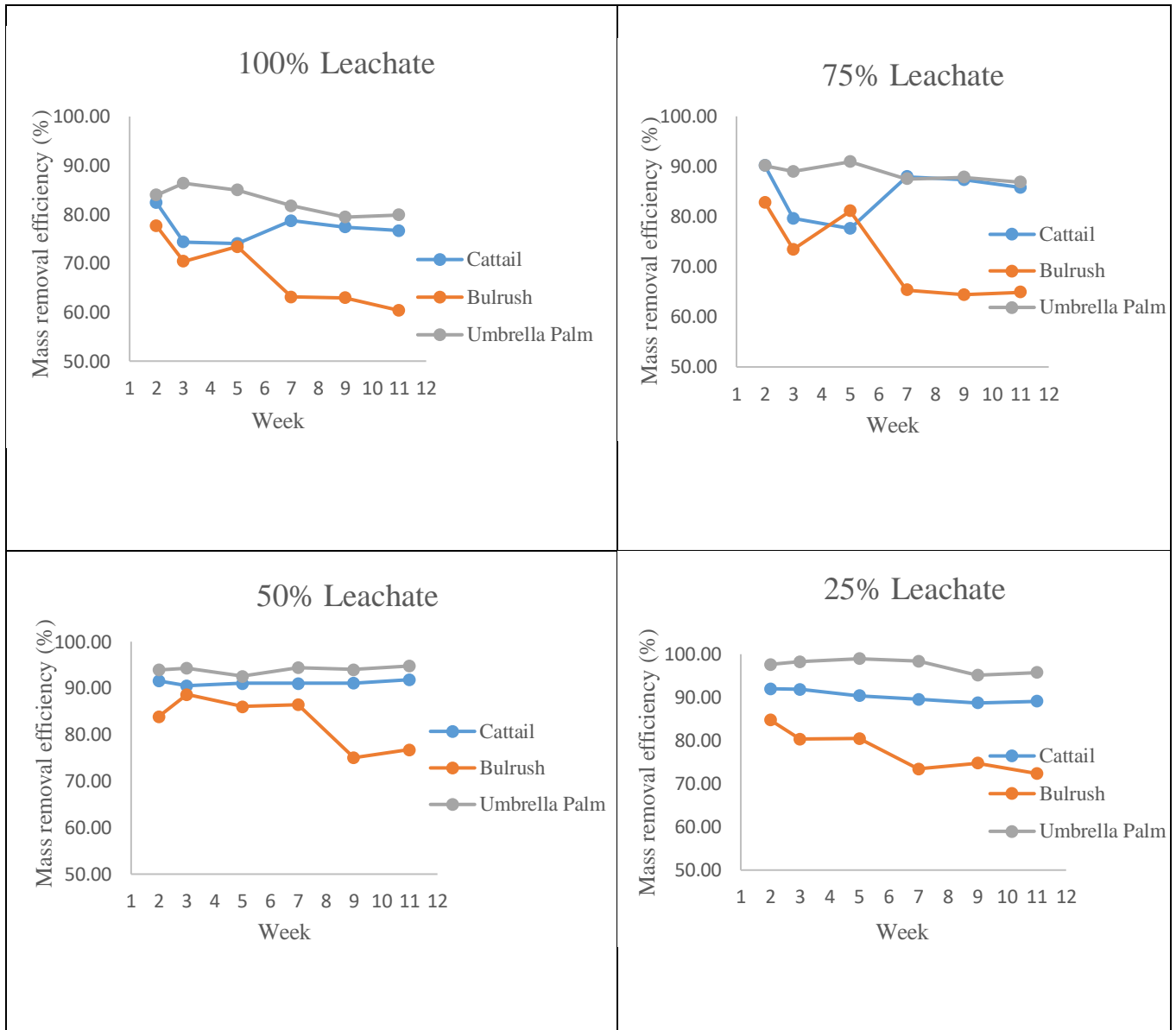


Figure 3.4: TC removal efficiencies in the presence of different plant species under different leachate loading

3.2.5 Phosphate (PO₄³⁻)

In CWs, PO₄³⁻ may be removed by plant uptake; therefore the type of plant species may have a great influence on PO₄³⁻ removal.

All three systems showed a high PO_4^{3-} removal capacity of above 88%. The highest PO_4^{3-} removal efficiencies (96.16-98.45%) were observed in Umbrella palm planted models, regardless of the leachate concentration, while Green bulrush exhibited the lowest performance (88.70-94.41%). The highest average removal efficiency was registered by Umbrella palm at 25% leachate concentration.

As the p-values of plant species, leachate concentrations and interactions are less than 0.05, it can be concluded that significant differences in PO_4^{3-} removal efficiencies are existing among those parameters (Figure 3.5).

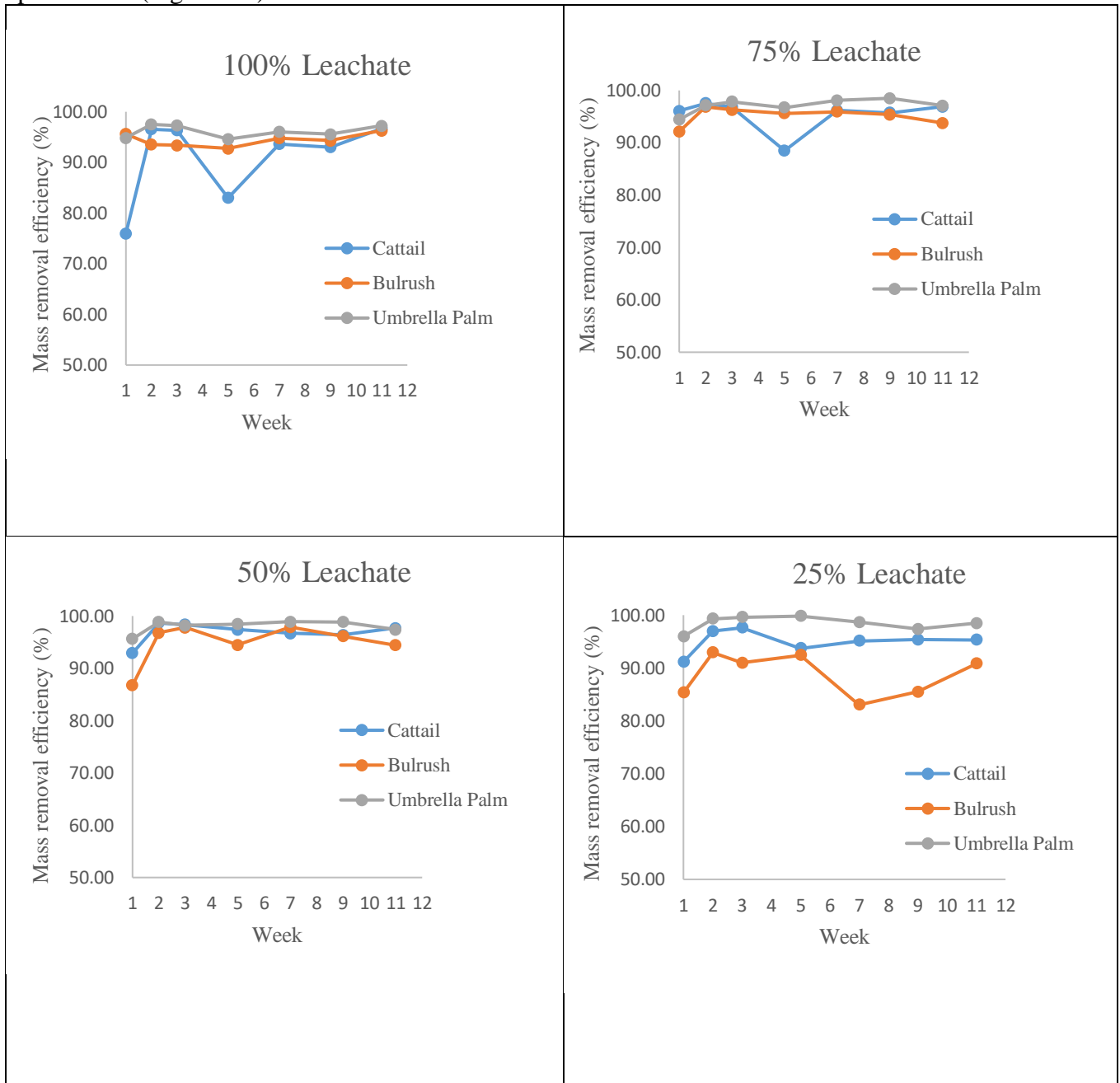


Figure 3.5: PO_4^{3-} removal efficiencies in the presence of different plant species under different leachate loading

3.3. Effluent standard

To find out the optimal concentration of leachate to be fed to CWs, the effluent COD and BOD₅ values of each system were compared with the Central Environmental Authority (CEA) discharge standards (Gazette No. 1534/18, 2008). The CEA effluent discharge standards for COD and BOD₅ are 250 mg/L and 30 mg/L, respectively. It was observed that both standards were satisfactorily achieved in CWs planted with Umbrella palm and fed with 25% and 50% leachate concentrations. But CWs with other plant species were capable of achieving the COD and BOD₅ permissible discharge levels only in systems fed with 25% leachate concentration.

4. Conclusions

Twelve (12) identical SSF CW models were planted with 3 plant species and fed with 4 different leachate concentrations. Stock synthetic leachate solution was prepared and diluted to 4 concentrations (25%, 50%, 75% and 100%) as the feed solutions. Pollutant (COD, BOD₅, TN, TC and PO₄³⁻) removal efficiencies obtained from several batch tests were subjected to two-way ANOVA analysis and statistical differences among systems were assessed. The mean comparisons were performed using basic statistical analysis to find out the best plant species and best feed concentration. Effluent concentrations were compared against permissible discharge standards.

Fluctuations in removal efficiencies were observed in all tested models, which is normal in any living biological system. All 3 plant species performed satisfactorily well for leachate concentrations of 25% according to the CEA permissible discharge standards. The highest average pollutant removal efficiencies were observed in CWs planted with Umbrella palm (*Cyperus alterifolius*) for all leachate concentrations.

The result of Two way ANOVA tests indicated that a significant difference exists among the three plant species and four feed concentrations in removing all tested pollutant parameters. Therefore, mean comparisons were performed to find out the plant species and concentrations corresponding to the best treatment.

Umbrella palm exhibited the best removal efficiencies for all parameters irrespective of leachate concentration. The results gained from two way ANOVA comparing the performance of the plant species independent of leachate concentration also proved that the same plant species is significantly efficient, in treatment of leachate.

Mean Comparisons were performed using Minitab software to find the concentration corresponding to the best treatment efficiency irrespective of the plant species. The best removal efficiencies in removing BOD, COD and TN were given by 25% leachate, while 50% leachate has been given the best removal efficiency of TC and PO₄³⁻.

Evapotranspiration studies recorded a significantly higher loss for all plant species at all leachate concentrations. This was attributed to the tropical climate conditions of the study location. The significant differences among the ET potential for different plant species were observed. Evapotranspiration rates were also significantly changed with the leachate concentration. The highest ET loss rate was reported in CWs containing umbrella palm plants and fed with 25% leachate.

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