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Performance of a vertical subsurface flow constructed wetland under different operational conditions

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A B S T R A C T

The performance of a vertical subsurface flow constructed wetland (VSSFCW) for sewage effluent treatment was studied in an eight month experiment under different operational conditions including: vegetation (the presence or absence of common reeds "*Phragmites australis*"), media type (gravel or vermiculite), and mode of sewage feeding (continuous or batch). Plants had a significant effect ($P < 0.05$) on the removal efficiency and mass removal rate of all pollutants, except phosphorous. The average removal efficiencies of chemical oxygen demand (COD), biological oxygen demand (BOD), total suspended solids (TSS), ammonium (NH_4) and total-P (TP) were 75%, 84%, 75%, 32% and 22% for the planted beds compared to 29%, 37%, 42%, 26% and 17%, respectively, for the unplanted beds. The VSSFCW was ineffective in removing nitrate (NO_3). The effect of either media type or feeding mode system on the removal efficiency of COD and BOD was insignificant. Vermiculite media significantly ($P < 0.05$) increased the efficiency of the wetland in removing NH_4, TP and dissolved phosphorous (DP) when compared with gravel particularly in the planted beds. The batch mode was more effective in removing TSS and NH_4 compared to the continuous mode. Volumetric rate constant (k_V) was different for various pollutants and significantly increased due to the presence of plants. Media type had no significant effect on the values of k_V for COD, BOD and TSS, while k_V for NH_4 and TP under vermiculite in the planted beds and k_V for P in the unplanted beds were significantly higher than those under gravel.

Introduction

The traditional treatment of sewage effluent is very expensive, requires highly trained operators onsite at all times and does not work well on a small scale [1]. Constructed wetlands (CWs) are capable of reducing the treatment cost and the complexity of operation without sacrificing the degree of pollution control [2,3]. CWs are particularly useful for small communities in urban and rural areas with no access to public sewage systems [4]. Subsurface flow constructed wetlands (SSFCW)

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have demonstrated a consistent capacity to remove organic C and particulate matter from wastewater but have been less successful in the removal of N and P [5].

As SSFCW is a relatively new technology, the operational conditions that affect wetland performance are still poorly defined. The SSFCW can either be planted or unplanted. Several studies have shown that plants enhance treatment efficiency by providing a favorable environment for the development of microbial populations and by oxygenating the system [6–9]. However, Zhu et al. [10] determined that the presence of vegetation causes only minor variations in the efficiency of removing chemical oxygen demand (COD), total suspended solids (TSS), N and P from livestock wastewater. In addition, Coleman et al. [3] showed that gravel alone provides significant wastewater treatment, but vegetation further improves treatment efficiencies.

The high purification efficiency of constructed wetlands can be achieved by choosing suitable growth media. Particle size, surface nature, bulk porosity and pore spaces of the growth media are important factors in this respect [11]. Growth media provide not only physical support for plant growth but also additional sites for biofilm growth and the adsorption of nutrients and promote the sedimentation and filtration of pollutants [12,13]. Gravel is the most commonly used media in CW [1]. The results of Priya et al. [13] showed that sand provides a more efficient treatment than gravel. Sirianuntapiboon et al. [14] determined that the CW with media containing a soil and sand mixture yields the highest removal efficiencies of the pollutants. Several authors [15,16] use different types of media (e.g. vermiculite, zeolite, and lime) to remove certain compound from the wastewater. Constructed wetlands can be operated under continuous or batch feeding modes. The type of feeding mode affects the aeration conditions in the growth media. For example, batch feeding enables the diffusion of oxygen from the air into the bed [17,18]. The inconsistent treatment results concerning the presence of plants, type of media and mode of feeding of CW suggest that further research is needed to optimize the system performance.

Wetland performance is often evaluated on the basis of removal efficiency and the rate of pollutant removal. A first order equation that predicts an exponential decay between the inlet and outlet concentrations under constant influent conditions is used in constructed wetland design. The areal and volumetric rate constants of the model have been used by several authors [19,20,4] to simulate the behavior of the CW hydraulics and describe the removal performance for various pollutants. Few studies [21,22] analyzed the changes in the values of the removal rate constants due to changes in the operational conditions of the wetlands.

The objective of this study was to test the influence of vegetation condition, type of growth media and type of feeding mode on the performance of the VSSFCW, and to calculate the removal rate constants for each pollutant under these conditions.

Material and methods

Source of sewage

The raw sewage effluent in this study was supplied from the Zenien wastewater treatment plant in Giza, Egypt.

Construction of the VSSFCW

VSSFCW units were designed and located in Zenien wastewater treatment plant. The wetland units were constructed from plastic with the dimensions of $0.3 \times 0.3 \times 0.3$ m for length, width and depth, respectively, for an effective volume of $0.0225\ m^3$. The depth of the growth media was 0.25 m and the sewage level was 5 cm below the surface of the media. The raw sewage effluent was distributed vertically from the top of the unit and the treated sewage was collected from the bottom of the unit. The hydraulic retention time was 0.5 day and the hydraulic loading rate was $0.15\ m\ d^{-1}$. The performance of the wetland was tested, in an eight month experiment, under the presence and absence of plants, two types of growth media (gravel and vermiculite), and two modes of sewage effluent feeding (continuous and batch mode). The diameter of the gravel was 5–10 mm, and the porosity of the media was 30%. The vermiculite was obtained from an Egyptian company for vermiculite, its diameter was 5 mm and porosity of the media was 35%.

Initiation of the wetlands

Common reed plants (*Phragmites australis*) were used in this experiment. Healthy plants with a similar state of growth were collected from the Nile bank at Gezerit El Warak, Cairo, Egypt. The plants were cultivated in wetland units with rhizomes at a rate 6 plants/unit. After cultivation, the wetland units were fed with a diluted wastewater (50% tap water: 50% primary treated sewage effluent) for one month. Subsequently, the units were fed with only raw sewage effluent for one month. This sequence of operations was considered as a period for plant growth and establishment.

Calculations

The effect of different operational conditions on wetland performance was evaluated on the basis of percent removal, mass removal rate, areal removal rate constant and volumetric removal rate constant.

The percent removal (removal efficiency) was calculated as follows:

$$\text{Removal efficiency}\ (\%) = (C_{in} - C_{out})/C_{in} \times 100$$

where C_{in} and C_{out} = inflow and outflow concentrations, respectively ($mg\ L^{-1}$).

The mass removal rate (r, in $g\ m^{-2} d^{-1}$) was calculated as follows:

$$r = q\ (C_{in} - C_{out})$$

r = mass removal rate ($g\ m^{-2}\ d^{-1}$).
q = hydraulic loading rate ($m\ d^{-1}$).

Removal rate constants: A first-order degradation approach has been used to predict the removal performance of COD, BOD, TSS, N and P in the constructed wetlands. The rate constants for this model can be defined on either an areal (k_A) or a volumetric (k_V) basis.

The areal removal rate constant (k_A) was calculated using the equation proposed by [25]:

$$\ln(C_{out}/C_{in}) = -k_A/q$$

where

q = hydraulic loading rate (m day^{-1}) = Q/A,
Q = flow rate through the wetland (m^3 d^{-1}),
A = area of the wetland (m^2), and
k_A = areal removal rate constant (m d^{-1}).

The volumetric removal rate constant (k_V) was calculated using the equation proposed by [26].

$$\ln\,(C_{out}/C_{in}) = -k_v\ t$$

where

k_v = volumetric removal rate constant (d^{-1}),
t = hydraulic retention time in the wetland (d) = $V\mathcal{E}/Q$,
V = volume of the wetland (m^3), and
$\mathcal{E}$ = wetland porosity.

Methods of analyses

Samples of the sewage influents and effluents were collected two times per week. Throughout the course of the experiment over 8 months, total of 68 influent and effluent samples were collected. The samples were analyzed for TSS using a paper filtration method [23], COD using the open reflux method, BOD using the Winkler method, ammonium nitrogen (N-NH_4^+) using nesslerization method, nitrate nitrogen (N-NO_3^-) using the ultraviolet spectrophotometric screening method, soluble phosphate P (P-PO_4^{-3}) using the vanadomolybdophosphoric acid colorimetric method, and total phosphorus (TP) after digestion with nitric and sulfuric acids [24].

Statistical analysis

Multifactor analysis of variance (ANOVA) was applied to the removal efficiencies, the mass removal rate, and the areal and volumetric removal rate constants. When a significant difference was observed between treatments in the ANOVA procedure, multiple comparisons were made using the least significant difference (LSD) test for differences between means. A significance level of $P < 0.05$ was used for all statistical tests. The statistical tests were conducted using the ASSISTAT program version 7.7 beta [27].

Results and discussion

COD, BOD, and TSS removal

Figs. 1 and 2 show the concentration of COD, BOD, and TSS in the sewage influent and the corresponding values in the effluent after treatment in planted and unplanted VSSFCW throughout the course of the experiment. The dotted line in the figures indicates the Egyptian guidelines for the use of the treated sewage effluent in irrigation [28]. The composition of the influent varied widely throughout the experiment. Values fluctuated between 400 and 700 mg L^{-1} for COD, 150 and 300 mg L^{-1} for BOD and 100 and 350 mg L^{-1} for TSS. According to the limits defined by Thomas and Law [29] the strength of the raw sewage used in this experiment was classified as weak to medium sewage. The BOD/COD ratio in the influent ranged from 0.36 to 0.54, indicating that the raw sewage is fairly biodegradable and can be effectively treated biologically. Figs. 1 and 2 indicate that the wetlands were able to substantially decrease the level of COD, BOD, and TSS in the raw sewage effluent. The concentration of each pollutant in the effluent was directly related to the pollutant load of the influent. The curves show that the changes in the influent and effluent concentration for COD, BOD and TSS throughout the course of the experiment were parallel to each other, indicating the sewage strength is the major factor governing the ability of the wetland units to treat the sewage effluent.

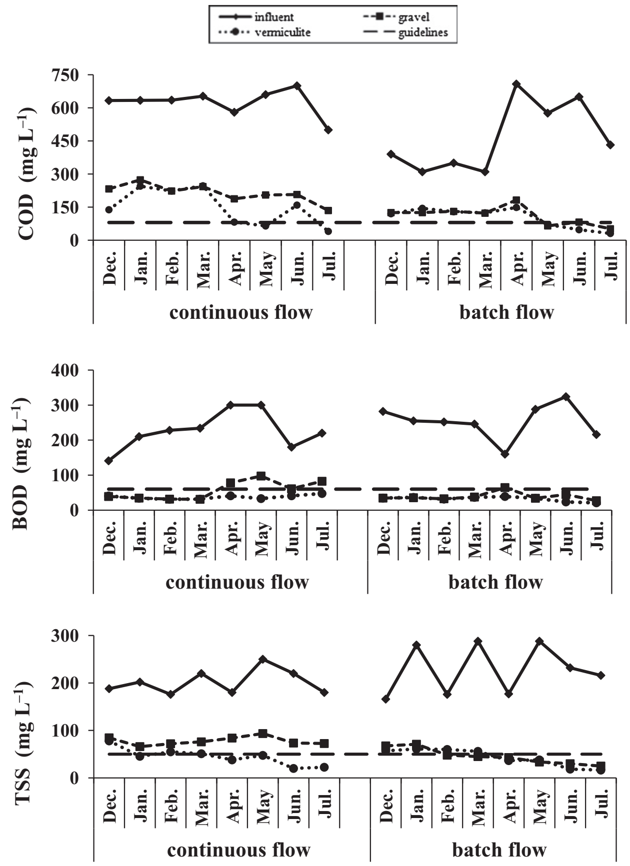

Fig. 1 Changes in COD, BOD and TSS concentrations in sewage effluent treated by planted constructed wetland units under different operational conditions.

The magnitude of the decrease in pollutant concentration upon treatment varied with the wetland operational conditions. Generally, the planted beds produced lower concentrations of COD, BOD and TSS in the effluent compared to the unplanted beds for all tested conditions. The concentration of COD, BOD, and TSS in the effluent treated by unplanted beds ranged from 260 to 362, 102 to 125, and 116 to 144 mg L^{-1}, respectively. These values were much higher than the standard concentration recommended by the Egyptian guidelines (COD~80, BOD~60, TSS~50). Although lower concentrations of pollutants were measured in the planted beds, only the levels of BOD and TSS in the effluent were lower than the recommended guidelines, whereas the COD level was much greater than the recommended guideline. Neither the type of media nor the feeding mode succeeded in producing effluent that fulfilled the required guidelines for reuse.

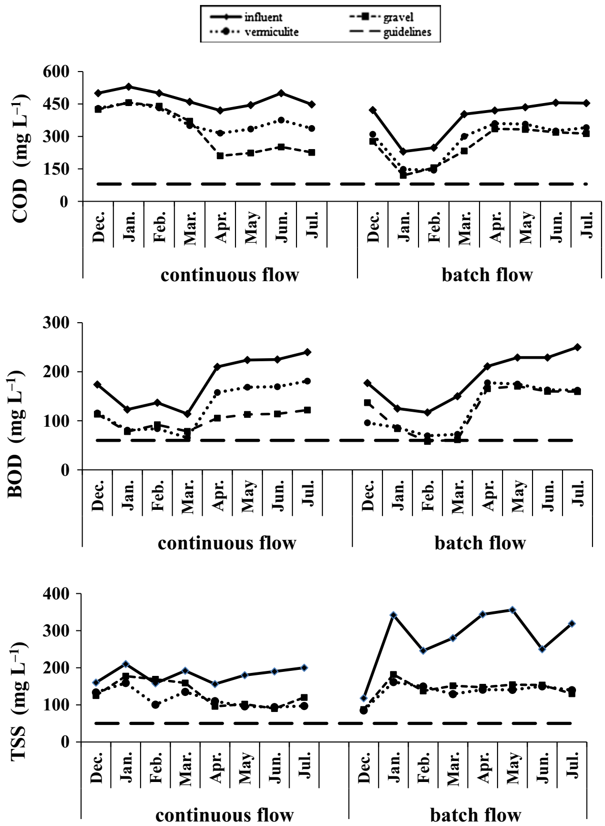

Fig. 2 Changes in COD, BOD and TSS concentrations in sewage effluent treated by unplanted constructed wetland units under different operational conditions.

The concentrations of each pollutant in the sewage influent and the resultant effluent throughout the course of the experiment were averaged (Tables 1–5). To compare the effect of different operational conditions on the performance of the wetland, the removal efficiency and mass removal rate were calculated and are provided in the tables. Table 1 shows that the planted beds removed an average of 75% of the COD load of the influent under different types of media and feeding modes. The average mass removal rate was 60.8 $g\,m^{-2}\,d^{-1}$. The unplanted beds were significantly less effective in removing COD, compared to the planted beds, as the percent removal and mass removal rate of COD were less than half and one third, respectively, of that removed by the planted beds. The effect of the media on COD removal varied with the vegetation conditions. In the planted beds the gravel and vermiculite media were equally effective in removing COD, while the gravel media in the unplanted beds was more efficient than vermiculite media. Statistical analysis showed that there was no significant effect of the feeding mode on the removal efficiency or removal rate of COD under vegetation conditions and type of media used.

Table 2 shows that the removal efficiency of BOD under all tested operational conditions was slightly greater than those previously recorded for COD. Vegetation plays an important and significant ($P < 0.05$) role in BOD removal; the average percent removal of BOD by the planted beds was 84%, compared to only 36% for the unplanted beds. Similarly, the average value of the BOD mass removal rate in the planted beds (30.1 $g\,m^{-2}\,d^{-1}$) was three times greater than in the unplanted beds (9.9 $g\,m^{-2}\,d^{-1}$). This discrepancy may explain the previous observation from Fig. 1 that the BOD level in the effluent from the planted beds was similar to or less than that recommended by the guidelines. Statistical analysis indicates that media type had no significant effect on BOD removal under either vegetation conditions or type of media used. Similarly there was no significant effect of the feeding mode on BOD removal under all conditions of vegetation or type of media. In general, batch feeding promotes greater oxidized conditions and therefore better performance for organic pollutant removal than continuous flow feeding [17,18]. The insignificant effect of the feeding mode on the removal of organic pollutant found in this study may be a result of the type of the constructed wetland used. In general, the VFCW is considered to be a highly aerobic system with high redox potentials that favor aerobic microbial processes [30]. It is possible that the prevailing redox conditions under the VSSFCW were not further improved by the batch mode of feeding particularly under the low HRT used in this study.

The mass removal rates of COD and BOD in the present study were similar to those reported by Zhao et al. [31] using the VSSFCW with alum sludge media and Dan et al. [32] using the HSSF and the VSSFCW with mixture media of gravel, coconut and sand.

The higher efficiency of the planted beds in removing COD and BOD compared to the unplanted beds indicates that plants were able to oxygenate the beds to a level that supports the aerobic degradation of the organic load of the sewage. In addition, the vegetation provides a substrate (roots, stems, and leaves) upon which microorganisms can grow as they break down organic molecules [33]. This community of microorganisms is known as the "periphyton". The periphyton and natural chemical processes are responsible for approximately 90% of pollutant removal and waste breakdown. The plants remove approximately 7–10% of pollutants, and act as a carbon source for the microbes when they decay [35]. However, despite the improved effluent quality for BOD by vegetation, the COD level was significantly ($P < 0.05$) higher than the level reported in the guidelines. The oxygen released from the roots was less than the amount needed for the aerobic degradation of the O_2 demanding molecule. A possible solution to increase the performance of the SSFCW is the artificial oxygenation of the bed. Another possible solution is to increase the residence time, but this will be accompanied by a significant reduction in the volume of the sewage treated in a given time.

Table 3 shows that among the three tested operational conditions of the wetland, both vegetation condition and feeding mode significantly ($P < 0.05$) affected the removal of TSS. The average percent removal of TSS (61–81%) for the planted beds was approximately 1.7 times that removed by the unplanted beds (34–51%). The mass removal rate of the TSS in the planted beds (24 $g\,m^{-2}\,d^{-1}$) was 1.6 times greater than that of the unplanted bed. The results of the mass removal rate for the TSS in the planted beds are similar to those reported by Zhao et al. [31] using the VSSFCW in planted bed with alum sludge media. The effect of feeding mode on the TSS removal efficiency varied with the type of media; in the planted beds, the batch mode of feeding was more effective in removing the TSS than the continuous mode under vermiculite, while under gravel media both types of feeding were equally effective. In the unplanted beds, the batch mode of feeding

Table 1 The effect of different operational conditions of constructed wetlands on the concentration of chemical oxygen demand (COD) in the sewage effluent, the removal efficiency, and the mass removal rate (r).

Vegetation conditions	Media type	Feeding mode	Influent (Avg ± SD) (mg L^{-1})	Effluent (Avg ± SD) (mg L^{-1})	Removal efficiency (%)	r (g m^{-2} d^{-1})
Planted beds	Gravel	Continuous	624 ± 40	187 ± 34	70^{a}	66.0^{ab}
		Batch	465 ± 76	110 ± 29	76^{a}	52.7^{b}
	Vermiculite	Continuous	624 ± 40	149 ± 33	76^{a}	70.5^{a}
		Batch	465 ± 76	101 ± 25	78^{a}	54.0^{b}
Contrast						
Gravel vs. vermiculite: ns			continuous mode vs. batch mode: ns			
Unplanted beds	Gravel	Continuous	475 ± 22	325 ± 21	32^{a}	22.2^{a}
		Batch	383 ± 38	260 ± 36	33^{a}	18.2^{b}
	Vermiculite	Continuous	475 ± 22	362 ± 26	24^{b}	16.7^{bc}
		Batch	383 ± 38	286 ± 4	25^{b}	14.4^{c}
Contrast						
Gravel vs. vermiculite: **			continuous mode vs. batch mode: ns			
Overall contrast						
Planted vs. unplanted			**			
Gravel vs. vermiculite			ns			
Continuous mode vs. batch mode			ns			

Note: (**) highly significant different and (ns) not significant.
Values within the same column followed by the same superscript letter are not significantly different at $P < 0.05$.

Table 2 The effect of different operational conditions of constructed wetlands on the concentration of Biological Oxygen Demand (BOD) in the sewage effluent, the removal efficiency, and the mass removal rate (r).

Vegetation conditions	Media type	Feeding mode	Influent (Avg ± SD) (mg L^{-1})	Effluent (Avg ± SD) (mg L^{-1})	Removal efficiency (%)	r (g m^{-2} d^{-1})
Planted beds	Gravel	Continuous	226 ± 21	38 ± 4	83[a]	27.5[a]
		Batch	253 ± 32	38 ± 7	85[a]	31.9[a]
	Vermiculite	Continuous	226 ± 21	37 ± 3	83[a]	28.0[a]
		Batch	253 ± 32	32 ± 4	87[a]	32.8[a]
Contrast						
Gravel vs. vermiculite: ns			continuous mode vs. batch mode: ns			
Unplanted beds	Gravel	Continuous	181 ± 8	102 ± 6	43[a]	11.6[a]
		Batch	186 ± 13	124 ± 19	33[a]	9.1[a]
	Vermiculite	Continuous	181 ± 8	114 ± 7	37[a]	9.9[a]
		Batch	186 ± 13	125 ± 10	33[a]	9.0[a]
Contrast						
Gravel vs. vermiculite: ns			continuous mode vs. batch mode: ns			
Overall contrast						
Planted vs. unplanted			**			
Gravel vs. vermiculite			ns			
Continuous mode vs. batch mode			ns			

Note: (**) highly significant different and (ns) not significant.
Values within the same column followed by the same superscript letter are not significantly different at $P < 0.05$.

Table 3 The effect of different operational conditions of constructed wetlands on the concentration of Total Suspended Solids (TSS) in the sewage effluent, the removal efficiency, and the mass removal rate (r).

Vegetation conditions	Media type	Feeding mode	Influent (Avg ± SD) (mg L^{-1})	Effluent (Avg ± SD) (mg L^{-1})	Removal efficiency (%)	r (g m^{-2} d^{-1})
Planted beds	Gravel	Continuous	202 ± 17	78 ± 5	61^{b}	18.3^{b}
		Batch	227 ± 50	45 ± 10	80^{a}	26.9^{a}
	Vermiculite	Continuous	202 ± 17	44 ± 10	78^{a}	23.4^{a}
		Batch	227 ± 50	42 ± 9	81^{a}	27.4^{a}
Contrast						
Gravel vs. vermiculite: ns			continuous mode vs. batch mode: *			
Unplanted beds	Gravel	Continuous	180 ± 18	119 ± 17	34^{b}	9.0^{b}
		Batch	281 ± 53	144 ± 21	48^{ab}	20.2^{a}
	Vermiculite	Continuous	180 ± 18	116 ± 10	35^{b}	9.4^{b}
		Batch	281 ± 53	136 ± 17	51^{a}	21.4^{a}
Contrast						
Gravel vs. vermiculite: ns			continuous mode vs. batch mode: **			
Overall contrast						
Planted vs. unplanted			**			
Gravel vs. vermiculite			ns			
Continuous mode vs. batch mode			**			

Note: (*) significant, (**) highly significant different, and (ns) not significant.
Values within the same column followed by the same superscript letter are not significantly different at $P < 0.05$.

Table 4 The effect of different operational conditions of constructed wetlands on the concentration of Ammonium (NH_4) and Nitrate (NO_3) in the sewage effluent, and the removal efficiency and the mass removal rate (r).

Vegetation conditions	Media type	Feeding mode	Influent (Avg ± SD) (mg L^{-1})	Effluent (Avg ± SD) (mg L^{-1})	Removal efficiency (%)	r (g m^{-2} d^{-1})
NH_4						
Planted beds	Gravel	Continuous	42 ± 10	34 ± 8	19^{c}	1.2^{b}
		Batch	33 ± 2	21 ± 0.8	36^{b}	1.7^{ab}
	Vermiculite	Continuous	42 ± 10	31 ± 5	26^{bc}	1.6^{ab}
		Batch	33 ± 2	17 ± 0.7	48^{a}	2.3^{a}
Contrast						
Gravel vs. vermiculite: **			continuous mode vs. batch mode: **			
Unplanted beds	Gravel	Continuous	30 ± 3	23 ± 3	22^{b}	1.1^{b}
		Batch	35 ± 3	27 ± 3	23^{b}	1.2^{b}
	Vermiculite	Continuous	30 ± 3	23 ± 4	22^{b}	1.1^{b}
		Batch	35 ± 3	22 ± 5	37^{a}	2.1^{a}
Contrast						
Gravel vs. vermiculite: ns			continuous mode vs. batch mode: ns			
Overall Contrast						
Planted vs. unplanted			*			
Gravel vs. vermiculite			ns			
Continuous mode vs. batch mode			ns			
NO_3						
Planted beds	Gravel	Continuous	6.1 ± 0.4	7.2 ± 1.0	−18	−0.16
		Batch	5.8 ± 1.5	7.1 ± 2.1	−22	−0.19
	Vermiculite	Continuous	6.1 ± 0.4	7.7 ± 1.7	−27	−0.24
		Batch	5.8 ± 1.5	7.6 ± 1.4	−31	−0.27
Unplanted beds	Gravel	Continuous	6.7 ± 1.0	6.7 ± 0.7	0	0.00
		Batch	5.2 ± 1.2	4.4 ± 1.2	15	0.12
	Vermiculite	Continuous	6.7 ± 1.0	5.9 ± 1.0	12	0.12
		Batch	5.2 ± 1.2	4.2 ± 0.8	19	0.15

Note: (*) significant, (**) highly significant different, and (ns) not significant.
Values within the same column followed by the same superscript letter are not significantly different at $P < 0.05$.

Table 5 The effect of different operational conditions of constructed wetlands on the concentration of Total-P (TP) and Dissolved-P (DP) in the sewage effluent, the removal efficiency, and the mass removal rate (r).

Vegetation conditions	Media type	Feeding mode	Influent (Avg ± SD) (mg L^{-1})	Effluent (Avg ± SD) (mg L^{-1})	Removal efficiency (%)	r (g m^{-2} d^{-1})
TP						
Planted beds	Gravel	Continuous	2.6 ± 0.3	2.1 ± 0.1	19^{bc}	0.066^{b}
		Batch	2.5 ± 0.14	2.1 ± 0.07	16^{c}	0.055^{b}
	Vermiculite	Continuous	2.6 ± 0.3	1.8 ± 0.1	31^{a}	0.121^{a}
		Batch	2.5 ± 0.14	1.9 ± 0.05	24^{ab}	0.088^{ab}
Contrast						
Gravel vs. vermiculite: **			continuous mode vs. batch mode: ns			
Unplanted beds	Gravel	Continuous	2.9 ± 0.1	2.7 ± 0.2	7^{b}	0.033^{b}
		Batch	2.6 ± 0.2	2.2 ± 0.3	15^{ab}	0.055^{ab}
	Vermiculite	Continuous	2.9 ± 0.1	2.3 ± 0.3	20^{a}	0.088^{a}
		Batch	2.6 ± 0.2	1.9 ± 0.3	27^{a}	0.099^{a}
Contrast						
Gravel vs. vermiculite: *			continuous mode vs. batch mode: ns			
Overall Contrast						
Planted vs. unplanted			ns			
Gravel vs. vermiculite			*			
Continuous mode vs. batch mode			ns			
DP						
Planted beds	Gravel	Continuous	1.5 ± 0.07	1.2 ± 0.14	20^{b}	0.044^{a}
		Batch	1.4 ± 0.14	1.1 ± 0.03	21^{b}	0.044^{a}
	Vermiculite	Continuous	1.5 ± 0.07	1.1 ± 0.04	26^{a}	0.055^{a}
		Batch	1.4 ± 0.14	1.0 ± 0.03	28^{a}	0.055^{a}
Contrast						
Gravel vs. vermiculite: **			continuous mode vs. batch mode: ns			
Unplanted beds	Gravel	Continuous	1.9 ± 0.36	1.7 ± 0.25	10^{c}	0.033^{b}
		Batch	1.5 ± 0.20	1.2 ± 0.08	20^{c}	0.044^{b}
	Vermiculite	Continuous	1.9 ± 0.36	1.3 ± 0.25	31^{b}	0.088^{a}
		Batch	1.5 ± 0.20	0.8 ± 0.02	47^{a}	0.099^{a}
Contrast						
Gravel vs. vermiculite: **			continuous mode vs. batch mode: ns			
Overall contrast						
Planted vs. unplanted			ns			
Gravel vs. vermiculite			*			
Continuous mode vs. batch mode			ns			

Note: (*) significant, (**) highly significant different, and (ns) not significant.
Values within the same column followed by the same superscript letter are not significantly different at $P < 0.05$.

demonstrated a higher efficiency on removing the TSS than the continuous mode under both gravel and vermiculite media. According to Vymazal et al. [4] suspended solids are mainly removed by physical processes such as sedimentation and filtration. Filtration occurs by the impaction of particles onto the roots and stems of the macrophytes or onto the soil/gravel particles in sub-surface flow systems. The effect of the feeding mode on the removal of TSS may be explained by its effect on the sedimentation rate of the suspended particles. In the batch mode of feeding the wetland system is filled with wastewater for a determined period of time and subsequently drained completely before the next batch of effluent is applied, whereas in the continuous mode the wastewater flows into the media continuously thus keeping it moist all the time. The batch feeding mode allowed more solids to be trapped in the pore spaces of the media compared to the continuous mode, resulting in higher values of TSS removal efficiency.

The statistical analysis revealed no significant difference between the two media types on TSS removal. The effect of vegetation on TSS removal is well documented [4,8]. Suspended solids primarily were removed by physical processes such as sedimentation and filtration. In the present work, common reeds grown in the wetland cells had an extensive root system that enhanced the TSS removal efficiency by providing a larger surface area, reducing the water velocity and reinforcing settling and filtration in the root network.

Nutrients removal

Table 4 shows that the NH_4 concentration of the influent was approximately five times greater than that of the NO_3. The initial concentration of NH_4 ranged 30–42 mg L^{-1} and decreases after treatment. The magnitude of the reduction varied with the operational conditions. In general, the removal efficiency of NH_4 under all tested conditions was low and followed the order: planted beds (32%) > unplanted beds (26%), the vermiculite media (33%) > gravel media (25%) and the batch feeding (36%) > continuous feeding (22%). Statistical analysis showed that there was no significant difference between the average concentration of NH_4 in the effluent of planted and unplanted beds (average 26 and 24 mg L^{-1}, respectively). The NH_4 concentration in the effluent is the result of the difference between the rate of its formation, due to organic N mineralization, and the rate of its removal, due to nitrification. The relatively high removal rate of NH_4 under planted vs. unplanted conditions could be explained by plant uptake and the higher rate of nitrification.

Data in Table 4 show that the NO_3 concentration in the effluent of the planted beds increased by 16% over that of the influent, while those of the unplanted bed decreased. This result implies that NH_4 uptake by plant is a minor factor compared to the nitrification process, which is considered the major NH_4 removal process. Statistical analysis ($P < 0.05$) showed that NH_4 removal was significantly affected by the type of media and mode of feeding in planted beds. The higher efficiency of NH_4 removal by vermiculite compared to gravel is possibly due to the higher cation exchange capacity (CEC) of the vermiculite that causes NH_4 adsorption via the cation exchange process. The batch mode of feeding may have caused better aeration conditions compared to continuous feeding [34]. Generally, the mass removal rate of NH_4 was very low, with an average of 1.7 and 1.4 g $m^{-2}d^{-1}$ for the planted and the unplanted beds, respectively, confirming the findings that the VSSFCW is not very successful in removing NH_4 [35].

The concentration of NO_3 in the influent was relatively low at approximately 5–6 mg/l. The effect of various operational conditions on NO_3 removal was not clear. The data show that the NO_3 concentration in the effluent of the planted bed slightly increased, thus producing negative removal percentages. This reflects high nitrification at the planted bed. In the unplanted beds NO_3 removal percentages were inconsistent and ranged from 0 to 19%. These low and inconsistent results for NO_3 removal reflect the absence of favorable conditions for its removal by the well aerated VSSFCW wetland. Nitrate is removed through its reduction to nitrogen gas by the action of the denitrification processes .This process occurs in the presence of available organic substance only under anaerobic and anoxic conditions, where nitrogen is used as an electron acceptor in place of oxygen [35]. The anaerobic conditions required for the onset of the NO_3 reduction are not fulfilled under the VSSFCW. These results are in accordance with those of Vymazal [35], who found that vertical flow constructed wetlands successfully remove ammonia N but very limited denitrification occurs. The VSSFCW offered good requirements of oxygen for the nitrification of NH_4 but unfavorable conditions for the denitrification of NO_3. A different requirement for the presence of oxygen for nitrification and denitrification is the major obstacle in many treatment wetlands for achieving higher nitrogen removal.

Data in Table 5 reveal low values for the initial TP concentration (2.6–2.9 mg L^{-1}) and the removal rate (7–27%). The effect of either the vegetation conditions or the feeding mode system on the removal efficiency was insignificant. However, the vermiculite media removed significantly ($P < 0.05$) higher amounts of TP (25.5%) compared to the gravel (14.2%), which could be caused by the adsorption of P on vermiculite surfaces. Vymazal [35] reported that the removal of P in all types of constructed wetlands was low unless special substrates with high sorption capacity were used. The overall mass removal rate of the TP was very low (approximately 0.07 g m^{-2} d^{-1}), indicating the low efficiency of the VSSFCW in removing P.

The concentration of the DP in the raw sewage ranged from 1.4 to 1.9 mg L^{-1} and on average represented approximately 60% of the TP. The wetland removed an average of 25% of the DP. Statistical analysis showed that only the type of media exerted a significant effect ($P < 0.05$) on the DP removal. The removal efficiency of the DP for the vermiculite media was approximately 2 times greater than for gravel. The average mass removal rate of the DP was 0.04 g m^{-2} d^{-1}, reflecting the low efficiency of the CW in removing nutrients. However, if the goal is to reuse the water for agricultural purposes, the low removal rate of P in this case is preferable, much as it is for N, as the nutrients will be available for the crops irrigated with the treated wastewater [36].

Removal rate constants

A first order model was used to describe the removal performance for various pollutants. The rate constants of the model, k_A and k_V, were calculated for COD, BOD, TSS, NH_4 and TP and provided in Table 6. Statistical analysis showed that the effect of the mode of feeding on the k_V values for the different

Table 6 The effect of different operational conditions of constructed wetland on the areal removal rate (k_A) and volumetric removal rate (k_V) of COD, BOD, TSS, NH_4 and TP.

Vegetation	Media type	COD	BOD	TSS	NH_4	TP
k_V (d^{-1})						
Planted beds	Gravel	2.64^a	3.68^a	2.59^b	0.66^b	0.40^b
	Vermiculite	2.95^a	3.85^a	3.27^a	0.96^a	0.66^a
Unplanted beds	Gravel	0.76^a	0.98^a	1.04^a	0.52^a	0.24^b
	Vermiculite	0.57^b	0.86^a	1.15^a	0.73^a	0.50^a
k_A ($m\ d^{-1}$)						
Planted beds	Gravel	0.20	0.27	0.19	0.05	0.03
	Vermiculite	0.22	0.29	0.24	0.07	0.05
Unplanted beds	Gravel	0.06	0.07	0.08	0.04	0.02
	Vermiculite	0.04	0.06	0.09	0.05	0.04

Values within the same column followed by the same superscript letter are not significantly different at $P < 0.05$.

pollutants was insignificant; thus, the data on the effect of the feeding mode were not presented. As the constants k_A and k_V are related to each other ($k_A = V/A\ k_V$), we will only discuss the data of k_V.

The removal rate is related to temperature, medium (the amount and type of organisms) and pollutant [37]. Table 6 shows that the value of k_V for each pollutant varied with the vegetation conditions and the type of media. In the planted beds the values followed the order: BOD (3.76) > TSS (2.94) > COD (2.79) > NH_4 (0.81) > TP (0.53) d^{-1}, whereas in the unplanted beds the values showed a similar trend with much lower magnitude: BOD (0.92) > TSS (1.09) > COD (0.66) > NH_4 (0.59) > TP (0.37) d^{-1}. The k_V constants for COD, BOD and TSS were similar to each other and were much higher than those of NH_4 and TP, thus confirming the low efficiency of the VSSFCW in removing N and P. Dan et al. [32] treated a mixture of domestic and pig farm wastewater using planted VSSFCW and reported comparable removal rate constants for COD and BOD and much higher values for NH_4 and TP. They found a positive significant effect ($P < 0.05$) of planting on the removal rate constants of pollutants.

Vermiculite media produced k_V values for COD and BOD that were not significantly different from those determined for gravel. The k_V values for TSS (3.27 d^{-1}), NH_4 (0.98 d^{-1}) and TP (0.66 d^{-1}) with the vermiculite media were significantly ($P < 0.05$) greater than those for the gravel media. Zidan et al. [21] and Chen et al. [22] studied the effect of different types of media on the removal of BOD and metals and determined that different media produced a different removal constant for the same pollutant. The removal rate constants of this study showed that the vermiculite and gravel media had different absorption efficiencies for NH_4 and P, which indicate that the removal efficiencies of NH_4 and P were influenced to a great extent by the choice of substrates. The first order removal kinetics obtained for BOD, COD, TSS, NH_4 and TP showed a coherent relation with previous findings of the positive effect of planting on the removal of all pollutants. Therefore, vegetation is an essential element to increase the performance of the VSSFCW.

Conclusions

Vegetation is a major factor that affects the efficiency of VSSFCW on removing COD, BOD, TSS and NH_4 under all tested conditions. The type of media is an important factor for the removal of NH_4, TP and DP, particularly in the planted beds. The mode of feeding had no significant effect in removing COD, BOD, TP and DP under all tested conditions. The batch mode of feeding has a significant ($P < 0.05$) effect only on TSS removal under gravel media in the planted bed and both media in the unplanted beds. The VSSFCW has low efficiency in removing NH_4, NO_3 and TP under all tested conditions.

Conflict of interest

The authors have declared no conflict of interest.

Compliance with Ethics Requirements

This article does not contain any studies with human or animal subjects.

Note

This paper is a remark on the Ph.D. thesis in the first order by Sara Gamal Abdelhakeem, Soil Science Department, Faculty of Agriculture, Cairo University.

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