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Dewatering and Treatment of Septage Using Vertical Flow Constructed Wetlands

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Received: 8 October 2017; Accepted: 25 October 2017; Published: 26 October 2017

Abstract: The vertical flow constructed wetland (VFCW) has become an attractive decentralised technology for septage treatment. One of the main purposes of the septage treatment is to reduce the volume of raw septage through dewatering, where the solids content is retained in the wetland bed and the water content is released. The retention of solids forms a layer of sludge deposit at the wetland surface, and the drained water, the so-called leachate, typically contains a lower solids content. This article reports the performance of dewatering and filtration of a pilot-scale VFCW designed for septage treatment. A comparison between two feeding strategies, hydraulic loading rate (HLR) and solids loading rate (SLR), is presented. The dewatering efficiency through drainage was found to be dependent on the solids load. The removal of total solids (TS) and chemical oxygen demand (COD) were excellent as the quality of leachate showed that more than 90% of TS and COD were retained in the system. This study reveals that the feeding based on SLR delivered a more sustainable performance for dewatering and solids removal. The build-up of sludge deposit significantly deteriorated the dewatering efficiency through drainage, but it tended to improve the filtration capacity.

Keywords: vertical flow constructed wetlands; septage treatment; dewatering; filtration

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1. Introduction

The individual septic tank (IST) is the main on-site sanitation system that is used in both urban and rural areas of developing countries. The sludge accumulated in the septic tank needs to be cleared periodically to maintain its treatment efficiency, and the mixture of sludge and blackwater removed from the septic tanks is known as septage. The solids and organic content of septage could be 10–100 times higher than municipal wastewater; hence, it has to be treated properly to reduce its contribution to environmental degradation [1]. Septage management is still a challenge in developing countries [2]. In Sarawak, a state of Malaysia, there are more than 370,000 individual septic tanks in operation, which serve approximately 1.9 million people in the entire state [3]. There are three centralised septage treatment plants located in the cities of Kuching, Sibu, and Miri. However, septage treatment in the towns of Sri Aman, Sarikei, Kapit, and Limbang are still at the planning stage, while the status of septage management for smaller towns is unknown. One of the concerns of septage treatment in these less-densely populated areas is the long distance between the household and treatment plant. A decentralised treatment technology is preferable to reduce the transportation expenditure.

The vertical flow constructed wetland (VFCW) has become an attractive decentralised technology for septage treatment due to its advantages of being reasonable in capital cost, efficient in energy consumption, and simple in operation [4,5]. The VFCW is an artificial system that delivers physical and biochemical processes at the same time. The raw septage is fed on the top surface of the wetland bed based on specific hydraulic or solids loading rate. Treatment occurs as the influent percolates through the substrate, which is a multi-layered granular bed filter. The particulate contaminants are physically retained at the top surface of substrate to form a layer of sludge deposit. The liquid released from the septage, the so-called leachate, is freely drained at the bottom of the substrate. In order to restore the aerated condition in the substrate, the VFCW is fed in batch, where the feeding is only carried out after the previous batch of influent has been completely drained.

The dewatering efficiency is an important parameter in the VFCW that is designed for septage treatment. The dewatering can be regarded as a solid-liquid separation mechanism to reduce the volume of raw septage, where the water content is diminished through drainage and evapotranspiration [6]. The presence of vegetation is found to be advantageous in enhancing the dewatering efficiency [7]. The remaining organic matter in the dewatered septage at the wetland surface are stabilised through microbial decomposition, which is the so-called mineralisation [8]. In order to optimise the dewatering efficiency, the control of solids loading is typically employed as the feeding strategy. This feeding regime is effective in tackling the fluctuating solids contents from batch to batch. The current literature indicated that the optimal solids loading rate is approximately 50 kg TS m^{-2} yr^{-1} in the temperate region [9,10], but it can be up to 250 kg TS m^{-2} yr^{-1} in the tropical region [11]. Nevertheless, such a feeding mode requires a preliminary test to measure the concentration of total solids (TS) in the raw septage, which increases the technical requirement of the system. Moreover, the raw septage with a low solids content may need to be fed with a volume that exceeds the capacity of the wetland bed, subsequently resulting in overload. Therefore, the control of hydraulic load is a more practical feeding strategy from the operation perspective [12]. Karolinczak and Dabrowski [13] indicated that the increase of hydraulic load tended to reduce the treatment efficiency of TS and organic matter, but it is effective for the removal of total nitrogen (TN).

In the VFCW, the particulate contaminant is physically filtered or settled in the substrate, while the dissolved organic matter and nutrient are degraded through microbial activities. The retention of solids at the wetland surface forms a layer of sludge deposit, which has been recognised as an effective porous medium to enhance the treatment performance [14]. Significant amounts of TS and chemical oxygen demand (COD) are retained in the wetland bed (at least 80% in most studies [9,11,13,15–17]) via physical filtration. However, the excessive accumulation of sludge deposit deteriorates the infiltration capacity of the wetland bed and extends the ponding period during operation, which eventually leads to the system failure, known as substrate clogging [18]. Furthermore, the removal of nitrogen compounds is less effective [13,15]. This is due to the aerobic characteristic in the substrate of the VFCW, where nitrification is promoted while denitrification is prohibited.

For septage treatment, the VFCW is categorised into a single-stage or a two-stage system. In the single-stage system, a sand layer is typically used in the substrate to enhance the treatment efficiency [9,10]. However, the sand characterises a low permeability that increases the risk of substrate clogging. Conversely, the wetland bed of a two-stage system is constructed using gravel, and requires sequential treatment to achieve the targeted quality [9,15–17]. The first stage treatment focuses on the dewatering and the removal of particulate contaminants by means of physical filtration, while the second stage treatment is to remove the dissolved contaminants within the effluent from first stage treatment through biochemical processes [16].

Although the current literature gained notable insights into the key parameters of the design and operation of the VFCW treating septage or sludge from other sources, studies in the tropical region is lacking as most researches were carried out in the temperate region [19]. Since there is no standard setup or design guidelines, specific uncertainties exist in responding to the septage characteristics and the local climate [20]. This article reports the performance of dewatering and filtration of the first stage treatment in a two-stage VFCW designed for septage treatment in Malaysia. A pilot-scale VFCW was constructed and operated in Miri, Sarawak to treat septage collected from local households. This study is divided into two phases, where Phase I was carried out with a feeding strategy based on the conventional solids loading rate (SLR). Then, Phase II involved feeding using the hydraulic loading rate (HLR) in order to investigate the possibility for simplification of the feeding strategy.

The monitoring of treatment performance focused on the removal of TS, COD, and total nitrogen (TN), and the influences of feeding strategy and sludge accumulation are discussed.

2. Materials and Methods

2.1. Phase I

In Phase I, two pilot-scale VFCWs were constructed using 400-gallon polyethylene water tanks. The substrate had a surface area of 2.20 m^2 and a height of 0.80 m. The substrate consisted of a (from bottom to top) 0.20 m coarse aggregates (diameter 50–60 mm), a 0.30 m medium-sized aggregates (diameter 30–45 mm), and a 0.30 m small-sized aggregates (diameter 8–10 mm). Three perforated pipes were installed vertically in the substrate for ventilation purposes. The common reeds (*phragmites karka*) were selected as the wetland plant since it is readily cultivatable and widely distributed in the local area, as well as its favourable characteristics of excellent productivity and extensive root development. At the beginning of the study, both wetland beds were acclimatised using both the wastewater and septage for six months to enhance the growth of wetland plants and the development of biofilm. This included acclimatisation as well as preliminary operation. Additionally, the acclimatisation could stabilise the wetland bed to ensure that a more consistent treatment can be obtained. The raw septage was collected from the household area and was stored in a polyethylene tank. The raw septage was screened using a wire mesh to remove gross solids that may damage the pumps and clog the substrate. The raw septage was homogenised and loaded to the wetland bed in a single batch. The SLR used in this study were 100, 250, and 350 kg TS m^{-2} yr^{-1}. The raw septage was fed on the wetland bed once weekly and the volume of the influent were determined according to the TS concentration. The actual loading rate to the wetland bed at the operation of 100, 250, and 350 kg TS m^{-2} yr^{-1} were 4.23, 10.58, and 14.81 kg TS, respectively. Each SLR was applied for eighteen runs except for 350 TS m^{-2} yr^{-1}, which was only tested for ten runs.

2.2. Phase II

Similar wetland beds were used for Phase II, as shown in Figure 1. The surface area for the Phase II wetlands were 1.1 m^2. The substrate configuration used was similar, but with smaller depths in the main layer (reduced to 0.27 m, with total substrate depth of 0.74 m). Ventilation was provided as before, and common reeds were used. The total acclimatisation period of the Phase II wetlands was similar to Phase I wetlands, with two months of acclimatisation, and three months of preliminary operation. Five hydraulic loads were used in this phase, which were 50, 75, 100, 125, and 150 L. Each HLR was applied for four runs except for 150 L, which was only tested for two runs.

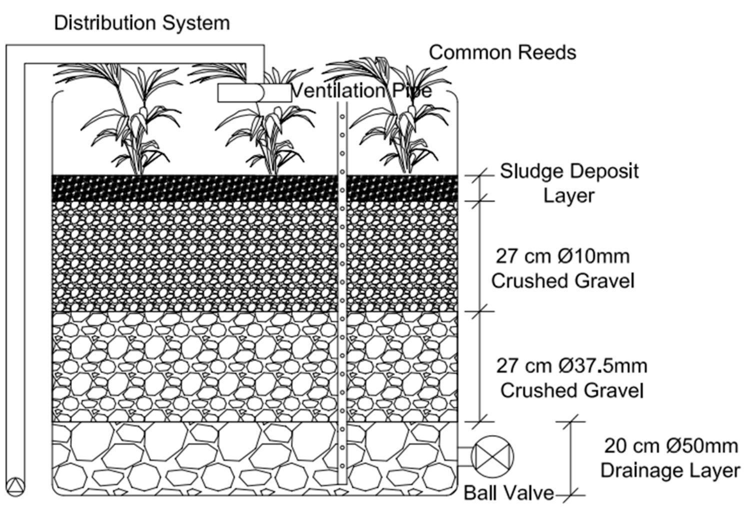

Figure 1. Cross section of Phase II wetlands.

2.3. Experimental Measurements

For both Phase I and Phase II wetlands, the leachate was collected from each bed for 24 h or until the flow rate became insignificant, after the raw septage was fed onto the bed. For Phase I wetlands, the total volume of effluent was measured to calculate the percentage of drained water. However, for Phase II wetlands, the effluent was sampled in intervals to study the dynamics of the flow. The total volume of the effluent may be obtained by the summation of each sample. The concentration of COD and TN were determined using HACH DR2800 spectrophotometer. The oven drying method was applied to measure the concentration of TS.

For Phase I wetlands, the removal efficiencies were obtained by determining the mass removal of each pollutant from the raw septage as:

$$mass\ removal\ efficiency\ (\%) = \frac{C_0 V_0 - C_e V_e}{C_0 V_0} \times 100\% \quad (1)$$

where C_0 is the influent concentration (mg L^{-1}), V_0 is the volume of influent (L), C_e is the effluent concentration (mg L^{-1}), and V_e is the total volume of effluent collected. Due to the mesocosm scale of the VFCW, it is assumed that the effects of the residual pore water and contaminants in the wetland bed was negligible in the analysis of the drained water and treatment efficiency. In addition, during the resting period, the wetland beds were allowed to drain freely. For the Phase II wetlands, because the effluent was sampled in intervals, the treatment efficiency was calculated with respect to each sample that was collected throughout the operation:

$$mass\ removal\ efficiency\ (\%) = \frac{C_0 V_0 - \sum_{i=1}^{N} C_{e_i} V_{e_i}}{C_0 V_0} \times 100\% \quad (2)$$

where i is the sampling sequence and N is the total number of sample collection.

3. Results and Discussion

3.1. Characteristics of Raw Septage

Table 1 presents the characteristics of twenty-eight batches of raw septage in Phase I. The raw septage in the feed tank was homogenised using a stirrer before feeding, and it was sampled from the distribution device before reaching the wetland bed. The concentrations of TS were generally high, where the mean concentration (mean ± standard deviation) were 42,693 ± 29,812 mg L^{-1}. The high variation among the batches shows that the septage characteristic could be greatly affected by the desludging frequency, water supply pattern, tank dimension, climate, and local custom [1]. In the meantime, the high standard deviation also implied that the characteristic of the raw septage were highly variable throughout the operation. The mean concentration of COD and TN were measured to be 35,526 ± 21,002 mg L^{-1} and 988 ± 381 mg L^{-1}, respectively. In Phase II, eighteen batches of raw septage were applied and the characteristics are presented in Table 1. The TS concentration obtained in this phase was much lower than Phase I, which was only 9439 ± 6646 mg L^{-1}. The mean concentration of COD and TN were also relatively low, which were 4549 ± 2477 mg L^{-1} and 192 ± 104 mg L^{-1}, respectively. The wide variation of septage quality was also reported in many studies [5,13,17].

Table 1. Characteristics of raw septage (mean ± standard deviation) in Phase I and Phase II of the experiment.

TS (mg L^{-1})	COD (mg L^{-1})	TN (mg L^{-1})
	Phase I (*n* = 28)	
42,693 ± 29,812	35,526 ± 21,002	988 ± 381
	Phase II (*n* = 18)	
9439 ± 6646	4549 ± 2477	192 ± 104

3.2. Dewatering Efficiency

The purpose of sludge dewatering is to reduce the septage volume as much as possible, where the solids content generally increased from 1–4% to 20–30% [21]. This is done by separating the solids from the raw septage, resulting in sludge deposit forming at the wetland surface and leachate discharging from the bed. Discharge of the leachate from the bed is a rapid mechanism, which can be done in 1–2 days after feeding. Then, the remaining water content in the sludge deposit is eliminated by means of evaporation and transpiration during the resting period, which typically takes up to a week to complete. Although maximising the dewatering through evapotranspiration is advantageous in reducing the costs of handling and treatment for leachate, a longer resting period is needed to achieve targeted performance, which decreases the productivity of the system at the same time. Accordingly, the drainage capacity is a key aspect of the dewatering performance in the VFCW designed for septage treatment.

Table 2 presents the results of the percentage of drained water from every feeding in Phase I. Due to the varying septage characteristics from batch to batch, the hydraulic loads were highly variable. For instance, the hydraulic loads of 100 kg TS m^{-2} yr^{-1} ranged from 54.24 L to 528.85 L, where the mean was 167 ± 113 L. The mean hydraulic load of 250 and 350 kg TS m^{-2} yr^{-1} were 396.80 ± 285.39 and 401.22 ± 243.97, respectively. However, the variation in hydraulic loads did not significantly affect the percentage of water, whereas it appeared that a greater percentage of drained water was associated with a lower SLR being applied to the system. Under the SLR of 100 kg TS m^{-2} yr^{-1}, 55–80% of raw septage was dewatered through draining, where a mean of 66.56 ± 6.90% was obtained. As for SLR of 250 kg TS m^{-2} yr^{-1}, the percentage of drained water is typically below 50% of the influent, where the mean was 43.28 ± 9.21%. The mean percentage of drained water for the SLR of 350 kg TS m^{-2} yr^{-1} was only 22.82 ± 8.27%. These results revealed that the dewatering efficiency of VFCW significantly depends on the applied SLR.

Table 2. Dewatering efficiency in Phase I of the experiment.

Case *	100 kg TS m^{-2} yr^{-1} (Solids Load = 4.23 kg)		250 kg TS m^{-2} yr^{-1} (Solids Load = 10.58 kg)		350 kg TS m^{-2} yr^{-1} (Solids Load = 14.81 kg)	
	Hydraulic Load (L)	**Percentage of Drained Water**	**Hydraulic Load (L)**	**Percentage of Drained Water**	**Hydraulic Load (L)**	**Percentage of Drained Water**
A	133.80	69.00%	334.50	46.00%	563.54	38.40%
B	202.43	67.00%	506.07	37.00%	207.48	34.30%
C	110.17	58.00%	275.43	40.00%	283.80	23.90%
D	112.52	63.00%	281.30	47.00%	521.36	26.80%
E	112.52	65.00%	281.30	49.00%	954.34	17.90%
F	183.53	77.00%	458.83	64.00%	153.36	26.20%
G	303.02	57.00%	757.55	49.00%	258.80	17.40%
H	167.87	59.00%	419.69	42.00%	98.54	11.20%
I	159.06	73.00%	397.66	34.00%	552.86	15.70%
J	55.96	66.00%	139.91	41.00%	417.64	16.40%
K	114.18	79.00%	285.46	53.00%	-	-
L	183.95	81.00%	459.87	56.00%	-	-
M	113.73	69.00%	284.33	38.00%	-	-
N	98.39	63.00%	245.97	33.00%	-	-
O	528.85	66.00%	1322.12	36.00%	-	-
P	311.09	65.00%	777.71	32.00%	-	-
Q	65.09	59.00%	162.72	29.00%	-	-
R	54.24	62.00%	135.60	53.00%	-	-
mean ± standard deviation	**167.24 ± 112.57**	**66.56% ± 6.90%**	**396.80 ± 285.39**	**43.28% ± 9.21%**	**401.22 ± 243.97**	**22.82% ± 8.27%**

* Cases A-R represent the experimental runs (a total of 18 runs for 100 and 250 kg TS m^{-2} yr^{-1} whilst 10 runs for 350 kg TS m^{-2} yr^{-1}).

Table 3 presents the results of solids load, deposit thickness, and the percentage of drained water in Phase II. In this phase, feeding was based on the HLR, and hence the solids load fluctuated. For instance, the solids load for HLR 125 L varied from 525 g to 2325 g, where the mean solids load was 1309.50 ± 646.81 g. Due to the low solids content in the raw septage collected in this phase, the case with the greatest amount of solids content (2325 g) is even lower than the lowest SLR in Phase I (4231 g). Similar to Phase I, the dewatering efficiency was independent from the effect of hydraulic load. For instance, the percentages of drained water were 35.67% and 81.37% in the HLR of 150 L, where the mean was 58.52 ± 22.85%. Similar trends were also observed in the HLR of 50 L, 100 L, and 125 L, where the mean percentage of water recovery were 57.79 ± 19.90%, 59.51 ± 12.30%, and 22.94 ± 19.42%, respectively. The amounts of drained water were relatively consistent under the HLR of 75 L, where the mean was 76.62 ± 6.98%. However, this observation is most likely due to the similar solids load and deposit thickness in these cases. In contrast, the low average percentage of drained water under the HLR of 125 L was attributed to the higher solids load and thicker sludge deposit throughout the experiment. These results revealed that the control of hydraulic load has a limited effect on the dewatering efficiency through drainage. This finding is the same as in [22], where the effect of HLR was found to be insignificant to the hydraulic behaviour. In this phase, the influence of solids load was insignificant. For instance, case 100A and 100C had the same HLR and a similar solids load, but the percentage of drained water of case 100A (73.41%) was much lower than case 100C (46.94%). In addition, the case with the greatest solids load under a particular HLR, i.e., 125D, did not demonstrate the poorest dewatering efficiency. On the other hand, the dewatering through drainage was found to be dependent on the deposit thickness. For instance, the percentage of drained water of cases 125A, 125B, and 125C were below 15% due to the significant amount of sludge deposit during the feeding (≥0.09 m). Instead, the percentage of drained water of case 125D increased to 56.43% due to a thinner deposit layer, which was only 0.05 m. The percentage of drained water with deposit thickness generally greater than 0.08 m were found to be below 50%, i.e., cases 50C and 100C. However, some cases with a thin deposit layer such as case 100D (0.03 m) and 150B (0.04 m) were observed to have water recovery below 50%.

Table 3. Dewatering efficiency in Phase II of the experiment.

Case *	Deposit Thickness (m)	Solids Load (g)	Percentage of Drained Water
50A	0.03	390	62.48%
50B	0.04	445	67.43%
50C	0.10	1200	24.49%
50D	0.06	735	76.77%
mean ± standard deviation	**0.06 ± 0.03**	**692.50 ± 320.98**	**57.79% ± 19.90%**
75A	0.05	120	68.14%
75B	0.06	360	71.92%
75C	0.07	105	85.87%
75D	0.05	795	80.55%
mean ± standard deviation	**0.06 ± 0.01**	**345.00 ± 278.81**	**76.62% ± 6.98%**
100A	0.06	1280	73.41%
100B	0.05	460	70.10%
100C	0.08	1260	46.94%
100D	0.03	1950	47.59%
mean ± standard deviation	**0.06 ± 0.02**	**1237.50 ± 278.81**	**59.51% ± 12.30%**
125A	0.12	1188	14.57%
125B	0.09	525	9.72%
125C	0.12	1200	11.04%
125D	0.05	2325	56.43%
mean ± standard deviation	**0.10 ± 0.03**	**1309.50 ± 646.81**	**22.94% ± 19.42%**
150A	0.03	480	81.37%
150B	0.04	225	35.67%
mean ± standard deviation	**0.04 ± 0.01**	**352.50 ± 127.50**	**58.52% ± 22.85%**

* Cases A–D represent the experimental runs (a total of 4 runs for 50, 75, 100, and 125 L per loading whilst 2 runs for 150 L per loading).

In Phase I, the thickness of the sludge deposit was not measured. However, the conditions of the wetland bed were assumed to be the same at the commencement of experiment. Hence, the build-up of sludge deposit was associated with the amount of solids that were applied to the bed. The higher the SLR, the more the sludge deposit accumulated. The accumulation of sludge deposit deteriorates the infiltration capacity of the wetland bed, resulting in poor dewatering efficiency by draining [14]. This explains the low percentage of drained water that was achieved in cases with SLR of 350 kg TS m^{-2} yr^{-1}. Due to the fluctuating solids content of each load, it is not possible to regulate sludge accumulation using the HLR feeding strategy. Although the HLR provided an easy feeding strategy to operate the VFCW without troublesome preliminary work, the operation based on the SLR is more sustainable from the perspective of dewatering efficiency.

By neglecting the treatment efficiency, a higher SLR tends to increase the productivity of the VFCW in treating septage. However, the relatively poor dewatering through drainage implies that a longer period may be required to eliminate water content through evapotranspiration, which highly relies on the local climate of the treatment plant. This explains why the SLR in tropical regions [12,23,24] could be higher than those in the temperate region [9,10,17]. As the duration of resting period is determined by the time needed to dry up the sludge deposit, a longer resting period actually reduces the overall productivity of the system. It should be noted that the sludge deposit experienced a transformation from plastic state to solid state throughout the dewatering process [25]. Under the solid state, the sludge deposit easily cracks due to the continuous loss of water content (as shown in Figure 2), which restores a certain level of infiltration capacity due to the formation of "preferential pathway" for the influent. Kim et al. [17] also highlighted the high deformability of deposit layer due to the young age of the beds. In order to achieve the targeted dewatering performance, it is essential to take these considerations into account in designing the feeding strategy.

Figure 2. Formation of cracks in the sludge deposit layer during the resting period. These cracks restored a certain level of infiltration capacity due to the formation of "preferential pathway" for the influent.

3.3. Solids Removal

According to Table 1, raw septage typically contained a high concentration of particulate pollutants. In the VFCW, the granular substrate acts as a filter to physically trap the solids components. As for the system designed for septage treatment, the presence of a sand layer in the substrate profile [12,13] remains controversial as it increases the risk of substrate clogging. Therefore, it is crucial to determine whether the substrate built by coarse materials is adequate to deliver reliable treatment performance.

Table 4 presents the treatment efficiency of TS, COD, and TN in Phase I under varying SLR. The treatment efficiencies of TS, COD, and TN in the proposed system were excellent, achieving 85% in most cases. The TS removal appeared to be more efficient under higher SLR, where the mean TS removal under 350, 250, and 100 kg TS m^{-2} yr^{-1} were 98.10 $\pm$ 1.18%, 95.54 $\pm$ 2.05%, and 92.68 $\pm$ 5.84% respectively. Similarly, the COD removals were the highest under the SLR of 350 kg TS m^{-2} yr^{-1}, where the mean was 98.03 $\pm$ 2.83%. However, the mean COD removal of 100 kg TS m^{-2} yr^{-1}

(97.28 ± 2.25%) was slightly higher than 250 kg TS m^{-2} yr^{-1} (96.37 ± 2.67%). On the other hand, the TN removals improved with an increasing SLR, where the mean efficiencies were 85.94 ± 5.96%, 88.35 ± 5.94%, and 94.69 ± 4.22% for 100, 250, and 350 kg TS m^{-2} yr^{-1}, respectively. As a result, a higher SLR was found to be beneficial in enhancing the treatments of TS, COD, and TN in the proposed VFCW system.

Table 4. Treatment performance in Phase I of the experiment.

Case *	100 kg m^{-2} yr^{-1} (Solids Load = 4.23 kg)			250 kg m^{-2} yr^{-1} (Solids Load = 10.58 kg)			350 kg m^{-2} yr^{-1} (Solids Load = 14.81 kg)		
	TS Removal	**COD Removal**	**TN Removal**	**TS Removal**	**COD Removal**	**TN Removal**	**TS Removal**	**COD Removal**	**TN Removal**
A	90.07%	93.12%	82.69%	93.11	95.28%	87.31%	96.63%	89.96%	82.41%
B	88.38%	95.93%	87.44%	93.02	97.43%	92.82%	97.53%	97.95%	95.40%
C	93.12%	99.13%	79.45%	94.84	98.80%	85.21%	98.25%	98.98%	94.48%
D	95.98%	99.31%	86.61%	97.00	99.01%	88.63%	97.49%	97.75%	95.06%
E	96.74%	99.23%	91.59%	96.52	99.57%	93.33%	96.09%	97.25%	92.76%
F	95.99%	98.56%	89.46%	94.33	96.60%	91.10%	99.59%	99.73%	96.35%
G	95.10%	98.43%	92.85%	94.96	96.45%	90.79%	99.29%	99.52%	96.73%
H	95.22%	99.68%	88.57%	95.75	95.71%	84.28%	99.91%	99.92%	98.92%
I	94.48%	93.35%	75.27%	97.28	94.41%	85.74%	97.94%	99.69%	98.22%
J	95.81%	98.74%	95.33%	91.11	87.86%	95.94%	98.25%	99.50%	96.54%
K	93.41%	96.25%	82.91%	97.84	96.16%	87.54%	-	-	-
L	88.59%	95.89%	70.24%	96.25	96.41%	70.70%	-	-	-
M	93.62%	97.13%	92.37%	95.35	97.38%	96.85%	-	-	-
N	95.62%	97.11%	84.67%	96.74	96.47%	84.49%	-	-	-
O	72.74%	92.51%	88.49%	93.02	92.79%	92.26%	-	-	-
P	86.64%	99.29%	89.29%	95.11	99.41%	92.97%	-	-	-
Q	98.05%	98.71%	85.32%	99.04	98.02%	90.86%	-	-	-
R	98.61%	98.76%	84.33%	98.52	96.88%	79.48%	-	-	-
mean ± standard deviation	**92.68% ± 5.84%**	**97.28% ± 2.25%**	**85.94% ± 5.96%**	**95.54% ± 2.05%**	**96.37% ± 2.67%**	**88.35% ± 5.94%**	**98.10% ± 1.18%**	**98.03% ± 2.83%**	**94.69% ± 4.22%**

* Cases A-R represent the experimental runs (a total of 18 runs for 100 and 250 kg TS m^{-2} yr^{-1} whilst 10 runs for 350 kg TS m^{-2} yr^{-1}).

Table 5 presents the treatment efficiency of TS, COD, and TN in Phase II under varying HLR. Although three cases were observed with the TS removals below 80%, the overall performance throughout eighteen cases still resulted in a mean of 91.34 ± 7.11%. On the other hand, the COD removals achieved were more than 80% in all of the cases, where the mean treatment efficiency was 95.30 ± 4.79%. The treatment of TN was relatively poor, but it still achieved an average of 89.52 ± 8.70%. The influence of HLR was found to be minor throughout the experiment. For instance, the treatment performance of case 75A was significantly higher than case 75B, where the comparison of TS, COD, and TN removals of case 75A and 75B were 90.02% and 79.92%, 92.95% and 83.79%, and 96.56% and 80.87%, respectively. In addition, the TN removal of case 50A was much lower than the other cases under the same HLR. Also, the treatment of TS and TN in case 150B was significantly better than in case 150A. These outcomes revealed that the treatment efficiency of the VFCW system designed for septage treatment could be more dependent on the solids load and deposit thickness.

Similar to Phase I, Figure 3 shows that the removals of TS, COD, and TN in Phase II were improved with increasing solids load. When the solids load in the influent was below 500 g, the treatment performance fluctuated, particularly with TS and TN. In contrast, the removals of TS and COD remained above 90% when the solids load exceeded 500 g, whereas the treatment of TN attained more than 80% in these cases. Both phases of the experiment revealed the importance of solids load towards the treatment efficiency of the VFCW in treating septage. Moreover, a thick sludge deposit layer is advantageous to the treatment. For instance, the treatment efficiency of TS, COD, and TN in cases with remarkable deposit thickness (i.e., case 50C, 125A, 125B, and 125C) were typically above 95%. Nevertheless, this observation does not mean that the wetland bed with a thin sludge deposit layer will deliver a poor treatment. For instance, although the deposit thickness of case 50B was only 0.04 m, the removals of TS, COD, and TN achieved were more than 90%. However, based on the experiment, it is recommended that a sludge deposit of more than 0.08 m is favourable in performing consistent TS, COD, and TN removal.

Table 5. Treatment performance in Phase II of the experiment.

Case *	TS Removal	COD Removal	TN Removal
50A	92.35%	97.75%	68.22%
50B	93.20%	98.87%	92.08%
50C	98.14%	99.00%	95.10%
50D	94.23%	98.22%	94.14%
mean ± standard deviation	**94.48% ± 2.25%**	**98.46% ± 0.51%**	**87.39% ± 11.12%**
75A	90.02%	92.95%	96.56%
75B	79.72%	83.79%	80.87%
75C	78.30%	87.32%	77.32%
75D	95.21%	88.49%	96.57%
mean ± standard deviation	**85.81% ± 7.06%**	**88.14% ± 3.27%**	**87.83% ± 8.82%**
100A	92.28%	94.98%	83.37%
100B	86.42%	99.36%	97.92%
100C	93.18%	97.08%	89.52%
100D	98.06%	98.42%	95.59%
mean ± standard deviation	**92.49% ± 4.13%**	**97.46% ± 1.65%**	**91.60% ± 5.66%**
125A	99.65%	99.91%	96.96%
125B	96.99%	99.61%	96.99%
125C	98.47%	99.77%	98.03%
125D	96.96%	96.70%	91.51%
mean ± standard deviation	**98.02% ± 1.12%**	**99.00% ± 1.33%**	**96.62% ± 3.15%**
150A	76.17%	90.02%	76.84%
150B	84.82%	93.18%	83.80%
mean ± standard deviation	**80.30% ± 4.13%**	**91.60% ± 1.58%**	**81.82% ± 1.98%**

* Cases A–D represent the experimental runs (a total of 4 runs for 50, 75, 100, and 125 L per loading whilst 2 runs for 150 L per loading).

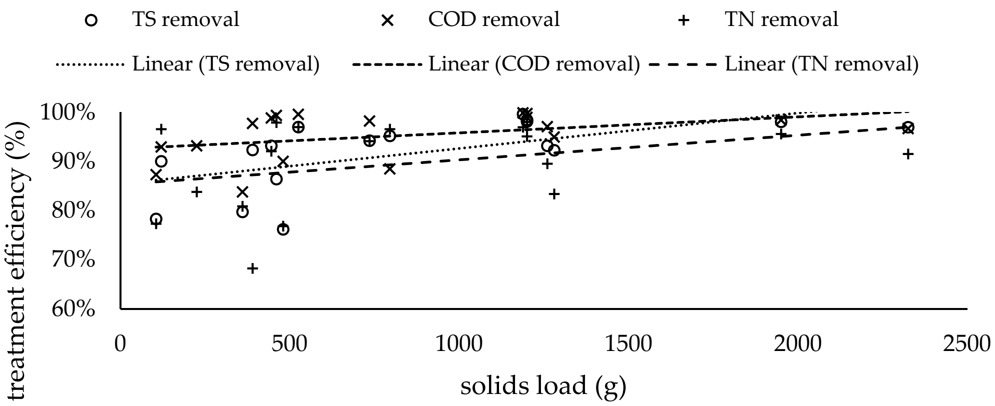

Figure 3. Influence of solids load on the removal of total solids (TS), chemical oxygen demand (COD), and total nitrogen (TN). The treatment performance were improved with the increasing solids load.

One of the greatest challenge of septage treatment is to remove the massive amount of particulate contaminants. In the VFCW, this can be simply accomplished through physical filtration. Figure 4 illustrates the concentrations of TS, COD, and TN in the leachate obtained from case 100B in Phase II. It shows that the TS concentration dropped substantially from 4600 mg L^{-1} to 1000 mg L^{-1} due to the excellent filtration capacity in the proposed system. The concentrations of COD and TN also significantly decreased in the early discharge, which dropped from 4203 mg L^{-1} to 219 mg L^{-1}, and from 150 mg L^{-1} to 30 mg L^{-1}, respectively. This observation indicated that the majority of organic matter and nitrogen compounds existed in the particulate form and were retained in the wetland bed. This is similar to the finding in [10], which highlighted that the treatment of COD depends more on the filtration when the water retention time is relatively short. The granular bed in the current system possesses a great filtration capability without a sand layer, where the treatment efficiency is comparable with the system with sand layer [12,22]. This is credited to the build-up of sludge deposit in the wetland bed, where this low-permeability layer is an effective filter for the solids content in raw septage.

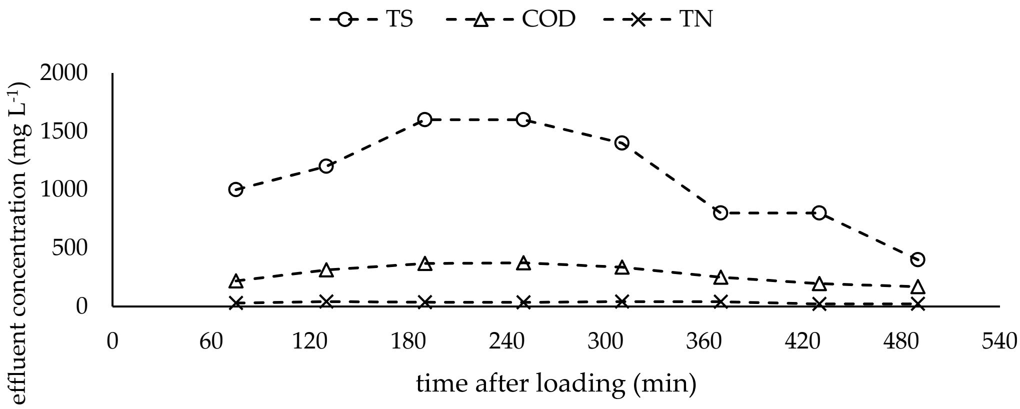

Figure 4. The dynamics of TS concentration (influent = 4600 mgL^{-1}), COD concentration (influent = 4203 mgL^{-1}) and TN concentration (influent = 150 mgL^{-1}) obtained from case 100B in Phase II of the experiment. The concentrations of these contaminants dropped substantially in the early discharge due to the physical filtration.

According to the experimental results, the influence of HLR on the treatment performance was found to be minor. On the other hand, the SLR was an efficient feeding strategy to optimise the removal of solids content. This observation agreed with the finding in [13], as the influence of SLR was found to be more significant than the HLR in removing solids, organic matter, and nitrogen compounds. As mentioned previously, a number of cracks were observed in the sludge deposit layer after the resting period. These cracks allowed the influent to "by-pass" the sludge deposit layer before entering the granular bed. Therefore, a higher solids load in the raw septage is advantageous to "seal" these cracks, subsequently improving the filtration efficiency. In summary, the feeding strategy of SLR delivers a more sustainable performance from the perspective of dewatering and solids removal. Although the operation based on HLR is technically simple and reduces the risk of overflow, the fluctuating solids content in the raw septage hinders it in becoming a practical feeding strategy for long-term septage treatment. The application of SLR is more efficient in controlling the accumulation of sludge deposit in the VFCW, and hence delivering a more consistent performance in dewatering and treatment. This study found that the sludge deposit significantly deteriorated the dewatering efficiency through drainage, but it is advantageous to improve the filtration performance.

Overall, the proposed VFCW performed well in dewatering the raw septage, but the leachate discharged from the wetland beds would require further treatment by using a second stage VFCW [17] or a conventional biological wastewater treatment system [13]. It should also be noted that the sludge deposit is required to be disposed when its accumulation meets the capacity of the wetland bed. This highlights another purpose of septage treatment: stabilisation of the volatile organic matter and nutrient remaining in the sludge deposit to make sure that it can be safely disposed [8]. The degradation of these pollutants, so-called mineralisation, depends on the microbial activities, which mostly occur during the resting period. In order to achieve a more sustainable treatment, a study on the behaviour of dewatering and mineralisation of sludge deposit during the resting period should be carried out.

4. Conclusions

The results presented in this article were obtained from the two phases of studies to evaluate the influence of SLR and HLR to the dewatering and treatment efficiency in the VFCW that is designed for septage treatment. The dewatering efficiency through drainage was found to be better under low SLR. In addition, the dewatering efficiency showed a dependency on the deposit thickness, where a thicker sludge deposit significantly reduced the amount of drained water. The formation of cracks potentially restored the infiltration capacity of the wetland beds, but it required further study to investigate the change of bed characteristics during the resting period. The feeding strategy based on either the SLR or HLR demonstrated excellent treatment of solids and organic matter. Nevertheless, the SLR was determined as a more efficient feeding strategy to control the removals of solids content, where a higher solids load was advantageous to the treatment performance. This was because the higher the solids load, the more the sludge deposit accumulated. The build-up of sludge deposit acted as an effective filter to physically trap the particulate pollutants in the wetland bed. From the perspective of dewatering and solids removal, the SLR was a more practical feeding strategy for long-term treatment. Overall, the proposed VFCW performed well in dewatering the raw septage, but the leachate that was produced required further treatment. In addition, a study on the behaviour of dewatering and mineralisation of sludge deposit during the resting period, as well as the influence of sludge deposit, is required to gain more insights into the sustainability of the VFCW system designed for septage treatment.

Acknowledgments: This study is supported by Faculty of Science and Engineering, Curtin University Malaysia. The authors would like to acknowledge Jason Jie Xiang Bui for his assistance in conducting the experiments.

Author Contributions: All authors contributed equally to this work.

Conflicts of Interest: The authors declare no conflict of interest.

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