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Septage Treatment Using Pilot Vertical-flow Engineered Wetlands System

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ABSTRACT

This paper presents a two-staged, pilot-scale vertical flow engineered wetland-based septage treatment system (VFEWs), which was designed and constructed in Curtin University Sarawak Campus to determine the system efficiency in treatment of septage. The treatment system consists of storage tanks, vertical flow wetlands, and a network of influent and effluent distribution pipes. The first stage of the VFEWs treatment system consists of three vertical flow wetlands placed in parallel to provide pre-treatment to raw septage to reduce solids and organic matters mainly by physical filtration and sedimentation processes. The percolate from the first stage is then further treated in the second stage, with four vertical flow wetlands, each with variation in operational regime and substrate (filter) type. The influences of various system and application-related parameters such as substrate material, presence of plants and plant types, and septage feeding practices (solid loading rate (SLR), batch and intermittent loading, and frequency of daily feeding) on pollutant removal efficiency were studied. Results from the first stage wetlands indicate that the removal of total solids and organic matter (BOD and COD) from the raw septage is promising (> 80%) at both SLR of 100 kg TS/m^2.yr and 250 kg TS/m^2.yr, respectively. However, a higher SLR decreased the average NH_3-N removal efficiency. The findings on bed clogging assessment during the study period are also presented in this paper. Validation and expansion of these results are carried out with ongoing assessments on the system performance.

Keywords: Vertical-flow, engineered wetlands, septage, dewatering, substrate materials, plants, feeding regimes, removal efficiency;

INTRODUCTION

Engineered wetlands (EWs) are rapidly emerging as a feasible method for treatment of wastewater due to their low investment costs and ease of operation and maintenance. In many sites, EWs are considered economically

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and ecologically viable alternatives to conventional methods of wastewater treatment. Engineered wetlands have been used in many applications, ranging from the secondary treatment of domestic, agricultural and industrial wastewaters to the tertiary treatment and polishing of stormwater and wastewater treated by means of activated sludge plants. Factors affecting the performance of an engineered wetland system are generally dependent on a variety of operational factors relating to the system itself and the influent characteristic, as well as the way it is applied to the bed (Prochaska et al., 2007). System-related factors include substrate type, size and depth (Torrensa *et al*., 2009), maturity of bed and climate (Merlin *et al.*, 2002). Other factors could be type of vegetation, system configuration and the sizing of the bed. The application-related factors include the hydraulic loading rate (HLR), sludge loading rate (SLR), influent concentration and the influent feeding regime. From literature, most studies published over the past five decades reported on the performance of engineered wetlands in the temperate or subtropical regions. In the recent years, however, there is an increase in research interests on exploring the potential of using EWs to treat wastewater in the tropical regions. Their elevated temperatures were found to be beneficial in increasing the treatment efficiency of the system comparing to the non-tropical systems. EWs in tropical regions has been reported to show organic and nutrient removal rates at almost a factor of 10 higher than in temperate regions (Diemont, 2006).

Engineered wetlands have also been used to treat high-strength organic wastes such as septage, a by-product of on-site wastewater sanitation system. Engineered wetlands designed for the treatment of septage feature a combination of traditional sludge drying beds with natural wetlands, which have been productively used for solids dewatering and stabilization in small cities across Europe and Asia (Burgoon *et al*., 1997; Cooper *et al*., 1996; Kengne *et al*., 2009). Malaysia produces over six million cubic meters of raw sewage and septage annually and this results in over 100,000 tonnes of stabilized sludge each year (AECOM International Development & Sandec/EAWAG, 2010). Treatment and disposal of septage has become a problem due to its rich pollutants concentration and being highly heterogeneous. Besides, conventional septage treatment is non-existent in many small cities and suburban areas in Malaysia, and septage is managed by disposal to nearby water courses. This management method causes pollution and damage to the receiving water body.

Several researchers (see Koottatep *et al*., 2005; Nielsen, 2003) have suggested the use of vertical flow engineered wetlands (VFEWs) to treat septage as a cost-effective and technically feasible approach for septage dewatering, stabilisation and mineralisation. Vertical flow engineered wetlands (VFEWs) are flat beds comprise of graded gravels or aggregates topped with or without sand and planted with vegetation (macrophytes). VFEWs are fed either intermittently in batches or continuously with influent wastewater onto the bed surface. Wastewater will percolate down through the substrate and be collected by a drainage network at the bottom. There are relatively few studies focusing on septage treatment with EWs in tropical regions. Koottatep T. from the Asian Institute of Technology (AIT), Thailand had studied the treatment of faecal sludge or septage by means of engineered wetlands (Koottatep & Polprasert, 1997; Koottatep *et al*., 2001a; Koottatep *et al*., 2005; Panuvatvanich *et al*., 2009).

From Koottatep's research, engineered wetlands have been found to be a promising and stable technology for septage treatment in tropical regions (Koottatep *et al*., 2001a). In one of his studies, 25 m^2 of pilot-scale wetland beds filled with 0.65 m sand-gravel substrate and planted with narrow-leaf cattails (*Typha augustifolia*) were used to treat septage collected from the Bangkok city, Thailand. Solid loading rate (SLR) of 80–500 kg TS/m^2.yr was applied every once to twice weekly onto the beds and an optimal SLR of 250 kg TS/m^2.yr were found to result in the highest total solid (TS), total chemical oxygen demand (TCOD) and total Kjeldahl nitrogen (TKN) removal. Further, a yard-scale experimental plant in Yaounde (Cameroon) was constructed and studied by Kengne to evaluate the treatment of VFEWs planted with *Echinochloa Pyramidalis* on faecal sludge dewatering ,beside experimenting on the effects of different SLRs on growth of the wetland macrophytes (Kengne *et al*., 2009). The study revealed that the system performed well for solid–liquid separation at loading rate of 100–200 kg TS/m2/yr, with an average dry matter content of biosolids ≥30% and pollutant removal efficiencies higher than 77%, 86%, 90%, 90% and 95% for ammonia (NH_4^+), total suspended solids (TSS), TS, TKN and COD, respectively.

In this paper, an engineered wetland-based pilot septage treatment system, which is built and still operating in Curtin University Sarawak Campus, Malaysia, is presented. Components of the treatment system are described along with the materials used and the septage application regimes practiced are explained. While the study is underway, the results presented in this paper focused only on the effects of variation of SLR on the first 8 weeks of plant operation of two of the pilot EW beds which act as the first stage of treatment in the system.

MATERIALS AND METHODS

Description of the Pilot-scale Treatment System

The project site is located beside the wastewater treatment plant in Curtin University Sarawak Campus in Miri, Sarawak, Malaysia. The system consists of pilot-scale vertical flow engineered wetlands (VFEWs) set in an open field that is exposed to sunlight and wind. A semi-transparent roof was constructed to shelter the system from rainfall to prevent stormwater from disturbing and affecting the experimental output due to dilution. The system is a 2-staged treatment comprises of vertical flow wetlands and storage tanks, as shown in Figure 1.

In the first stage, there are three VFEWs, each with a surface area of approximately 2.2 m^2 and a height of 1.3 m. Septage is stored in two elevated receiving tanks and is gravity-fed onto the first stage wetlands (wetland As) on a weekly basis through 3-inch PVC perforated pipes complete with stopcocks. The resulting filtrate is stored in the effluent collection tank before being piped onto the second stage wetlands (wetland Bs) for further treatment. Modified pumps and timers are used at the second stage to control the influent feeding frequency and volume of loading for each session. The macrophytes used in the study are *Phragmites Karka*, a common reed found in abundance in the local swamp areas. All the wetlands are equipped with vent pipes to prevent anaerobic environment in the substrate.

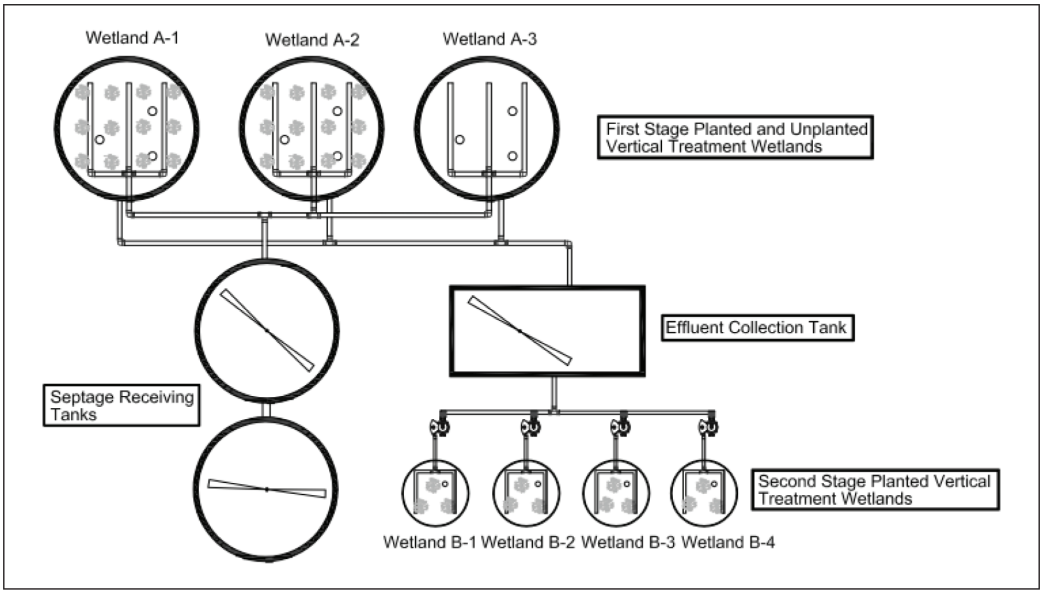

Fig.1. A schematic diagram of the pilot VFEWs system

Septage supply for the plant is obtained from a local environmental service provider and sourced from residential and communal septic tanks which receive only blackwater. Vacuum trucks loaded with raw septage visited the project site every 1-2 weeks to deliver the septage for the study. Coarse materials (>32mm) are removed from the septage by manual filtration using sieves to screen out the gross solids before storage. The septage is stored in two 400-gallon receiving tanks fitted with a mechanical mixer each to stir the septage to uniformity before being loaded onto the wetlands.

Crushed limestone is used as substrate in the vertical filter beds. The aggregate is a common construction material which is easily available locally for road construction. The total depth of the substrate in wetland As is 800mm, with 500mm freeboard for sludge accumulation. From bottom to top, the substrate filter consists of a 200mm layer of coarse aggregates (30–50mm diameter), a 300mm layer of medium aggregates (10-30mm diameter), and a 300mm layer of fine aggregates (3-8mm diameter). Wetland Bs are filled with limestone aggregates of 50mm thickness as the drainage layer (20-30mm diameter), overlaid by a 300mm thick intermediate stratum of palm kernel shell (PKS), topped with 300mm of pea gravel (3 mm) and finally covered by a layer of sand.

System Operational Regime

Wetland A1 – A3 are fed once in 7 days with nominal septage loads after the 6 months commissioning period. The septage is gravitationally loaded onto the beds for primary treatment before the resulting percolate is directed into an effluent collection tank for storage prior to further treatment by the subsequent wetlands (wetland B1 - 4). In the first stage wetlands, septage is applied in batches, with the wetlands receiving the influent in the range of 0.10 - 0.35 m3 (with respect to the designed SLR) in one go and within approximately 15 minutes. The outflow of the wetlands is controlled by stopcocks and water taps at the bottom of the basins. Table 1 indicates the operating conditions (Solid Loading Rate, SLR) at the first stage wetlands. Table 2 indicates the operating conditions at wetlands B1 – B4. The wetlands are loaded with percolate from the first stage, with the varying HLR as shown. Under the experimental regime, the wetlands are operated with intermittent loading (4 and 8 times of daily feedings) or with batch loading (up to 3 days flood : 3 days rest period). Wetlands are planted with either *Phragmites Karka* or *Costus Woodsonii* and contain substrate that is with or without PKS. At the time of writing, the experiments are still underway and only the partial results from operating the first stage wetlands are being presented in this paper.

TABLE 1
Operating conditions of the pilot VFEWs system (1st stage of the treatment)

Wetland	Description
A-1	100 kg TS/m^2. Yr (Planted)
A-2	250 kg TS/m^2. Yr (Planted)
A-3	250 kg TS/m^2. Yr (Unplanted)
All wetlands are filled with graded aggregates and vegetated wetlands planted with *phragmites karka*	

TABLE 2
Operating conditions of the pilot VFEWs system (2nd stage of the treatment)

Wetland	B1-B4	
Feeding and Draining Pattern	Intermittent Loading (Free drainage) No of daily feedings: 4, 8	Batch Loading (Cyclic effluent ponding and draining) Flood and Rest (Days): 1:1, 2:2, 3:3
Substrate	Sand and aggregates only; Sand and aggregates with PKS	
Macrophytes	Reeds: Phragmites Karka; Ornamentals: Costus Woodsonii	
HLR (cm/d)	8.75; 17.5	

PKS= Palm kernel shell
HLR = Hydraulic Loading Rate

Monitoring System Performance

The influent and effluent of each wetland at every stage were collected and analyzed weekly for the following water quality parameters: total solids (TS), total suspended solids (TSS), total volatile solids (TVS), total volatiles suspended solids (TVSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), total nitrogen (TN), nitrite-nitrogen (NO_2-N), nitrate-nitrogen (NO_3-N), and ammonia-nitrogen (NH_3-N) with HACH DR 2800 spectrophotometer based on USEPA approved standard procedure for wastewater analyses. Removal efficiencies are obtained by calculating the influent pollutant load reduction from the effluent at each treatment stage. *In situ* tests such as pH, temperature, dissolved oxygen (DO), oxidation-reduction potential (ORP) and electric conductivity (EC) were also carried out weekly on the influent before each feeding and effluents immediately after the collection.

A general assessment on clogging phenomena was carried out based on the visual observation as preliminary evaluation. The liquid fraction of the septage applied on the wetlands can infiltrate within a few minutes for well-drained substrate, to more than a week if the substrate is clogged. An observation was carried out on how noticeable the presence of standing water was on the beds days after septage application. A maximum of 3 days period for the draining of the liquid fraction was considered for well-drained substrate, 4 to 6 days for beds that were slightly clogged and more than 7 days for clogged beds.

For analysis of the collected results, one-way ANOVA tests were conducted to assess the effects of solid loading rate (SLR) on the pilot system's pollutant removal efficiencies. Post Hoc Multiple Comparisons test were also performed using Tukey's family error rate when necessary. The level of significance was set at $P<0.05$. The statistical software used was SPSS statistics 17.0 for Windows.

RESULTS AND DISCUSSIONS

Miri's Septage Characterisation

Septage is the combination of sludge, scum and liquid pumped from septic tanks. It is greatly heterogeneous and its concentration and organic matters content depend highly on users' habits, climate, septic tank size, and emptying frequency. Table 3 presents the characteristic of the raw domestic septage delivered to our VFEWs pilot plant, whereas Table 4 shows the characteristic of septage from different countries retrieved from the literature.

Our septage exhibited on average anaerobic or reducing conditions (<-200 mV) with high solids content and high organic and nutrient concentrations. Capillary suction time (CST) is the fundamental measure of the filterability and ease of removing moisture from sludge. Measured CST values for Miri's septage indicate a higher dewaterability in comparison to the septage from Andancette, France (Vincent *et al*., 2011), as shown in Table 4. Septage particle size, SS concentration and biochemical compositions (fats, protein and polysaccharides) are among factors that could influence the CST measurements (Jin *et al*., 2004; Vincent *et al*., 2011). Miri's septage has on average BOD:COD ratio of 0.09, which indicates low biodegradability due to decomposition of most degradable fractions after long storage time in the septic tanks. The characteristic of the septage from Miri is similar to that of the septage from Bangkok, as reported by Koottatep (see Table 4).

Plants and Wetlands Acclimatization

Preliminary planting trials were carried out to decide between two common wetland macrophytes, common reeds (*Phragmites Karka)* and cattail (*Typha Latifolia)* to be planted in the pilot system. Both the species were transplanted from the nearby river banks and monsoon drains into small pots by stem cutting for *Phragmites* and rhizome cutting for *Typha* on July 2011. The plants were planted in 37.5 mm aggregates and ponded with tap water for the first

TABLE 3
Physicochemical characteristics of Miri's septage

Parameter	N	Range	Average	Std
CST (s)	6	85.5-158.9	107.9	27.03
COD (mg/l)	14	12,400-54,870	33,442.19	13,963.70
BOD_5 (mg/l)	14	672-8,740	3,315.54	2,544.98
NH3-N (mg/l)	14	68-695	353.91	190.25
TKN (mg/l)	14	280-1,657	988	482.93
NO_3-N (mg/l)	14	5.39-35.7	14.53	9.18
TN (mg/l)	14	279-1,660	988.79	474.63
TP (mg/l)	6	275.9-2754	1,081.82	861.37
Temperature (◦C)	14	27.5-30.1	28.89	0.85
EC (ms/cm)	14	1.04-2.36	1.53	0.44
pH	14	5.93-7.69	6.82	0.51
DO (mg/l)	14	0.06-0.30	0.13	0.07
ORP (mV)	9	-100 to -546	-231.63	151
TS (mg/L)	14	13,962-57,600	32,588.50	14,954.44
TVS (mg/l)	14	8,054-59,318	21,888.21	12,556.11
TSS (mg/l)	14	5,200-50,500	23,875.38	12,121.11

N= No. of samples

1 month, after which the pots were drained and the plants were consistently watered with tap water on daily basis. After 3 months of growing period, it was observed that *Phragmites* had a faster growing rate than *Typha* in terms of number of emergent new shoots and plant height. Besides, *Phragmites* require less water to survive well, in terms of having minimal signs of wilting during the unponded period compared to *Typha.* Thus, *phragmites* was selected as the wetland macrophyte in our VFEWs system.

TABLE 4

Physicochemical characteristics of Septage from various regions

Parameter	N	Thailand*	N	Ghana**	N	Cameroon#	N	France##
CST (s)	-	N/A	-	N/A	-	N/A	-	360±142
COD (mg/l)	30	N/A	-	8,400	42	31,100	-	42,000±13
BOD_5 (mg/l)	30	2225±395	-	3,700	-	N/A	-	N/A
NH_3-N (mg/l)	30	320±70.89	-	500	42	600	-	287±76
TKN (mg/l)	30	N/A	-	N/A	42	1,100	-	1,423±435
NO_3-N (mg/l)	30	4.81±1.65	-	N/A	-	N/A	-	N/A
TN (mg/l)	30	950±99.18	-	N/A	-	N/A	-	N/A
TP (mg/l)	30	N/A	-	N/A	-	N/A	-	517±438
Temperature (°C)	30	28.67±1.5	-	N/A	-	N/A		N/A
EC (ms/cm)	30	N/A	-	17.27	44	2.79	-	N/A
pH	30	7.48±0.5	-	7.7	44	7.5	-	N/A
DO (mg/l)	30	N/A	-	N/A	-	N/A	-	N/A
ORP (mV)	30	-291±30	-	N/A	41	-54.2	-	N/A
TS (mg/L)	30	22,420±7702.6	-	11,800.00	44	3.7 (% DM)	-	30,000±10.6
TVS (mg/l)	30	N/A	-	6,726.00	43	64.4 (% DM)	-	21,300±2,100
TSS (mg/l)	30	19,500±7,250	-	N/A	-	N/A	-	23,0300±8,600

N/A= Not Available

N = number of samples

* Characteristics of septage from Bangkok, Thailand (Koottatep *et al*., 2005)

** Characteristics of septage from Kumasi, Ghana (Cofie *et al*., 2006)

\# Characteristics of septage from Yaoundé, Cameroon (Kengne *et al*., 2008)

\#\# Characteristics of septage from Andancette, France (Vincent *et al.,* 2011)

An engineered wetland is essentially an ecological system that requires time to establish itself before commencement of operation in which the full load will be introduced onto the substrate. There are varying guidelines in relation to the length of acclimatization, and these range from two to six months in the tropical climate (Ahmed *et al*., 2008; Trang *et al*., 2010). In our system, a six-month period was employed where the wetlands were progressively fed with diluted sludge every 3 days. This is to allow for plants and microbial community establishment besides preventing plants nutrient shock.

System Performance with Different SLRs

System Percolate

The results obtained from the preliminary experiments performed with the system are shown in Table 5. Removal of total solids and organic matter with the reduction in COD and BOD from the raw septage was the highest amongst the main parameters tested. Based on these preliminary results, it appears that variation in SLR has no significant effect on the removal efficiencies of these parameters at the 95% confidence level. This is because physical sedimentation and filtration were the major mechanisms for the removal of organic matters and solids from the system influent. Koottatep claimed that at a short hydraulic retention time (HRT), COD removal generally depends on filtration capacity of the wetland units rather than biological degradation of the organic matter (Koottatep *et al*., 2001b).

TABLE 5
Experimental results showing pollutant concentration and removal efficiency of wetland A1 and A2 with different SLR

Sample	Wetland (SLR in kg TS/m^2.yr)	Parameter*, mg/L					
		COD	*BOD*	*NH_3-N*	*NO_3-N*	*TN*	*TS*
Influent (Raw Septage)		31,957.71	3,592.50	427.99	13.26	1,209.20	24,573.60
Effluent (Resulting Filtrate)	A1 (100)	890.42 (96.87)	285.93 (91.92)	80.83 (79.24)	20.45	212.08 (80.12)	2,681.88 (89.97)
	A2 (250)	1,634.38 (94.5)	392.84 (87.86)	92.45 (76.79)	10.43	393.04 (76.01)	3,090.88 (88.81)
	F-value	1.966	2.064	4.767	-	2.932	0.305
	P**	0.183	0.173	0.047	-	0.109	0.589

* Percentage of removal as shown in parentheses were based on an average of 8 sets of data obtained from the 8 weeks of experimental run
** Significant at $P < 0.05$

Based on the statistical analysis of the data collected over a period of 8 weeks which reflected the system performance for the first 2 months, NH_3-N removal efficiency was found to vary according to different SLRs. At a loading rate of 100 kg TS/m^2.yr, ammonia removal was 79.24% and is significantly higher than that of the wetland fed with SLR of 250 kg TS/

m^2.yr which yielded a removal of 76.79% with $P<0.05$. In comparison with assimilation of organic matter by heterotrophic bacteria, autotrophic nitrification is a relatively more sensitive process which requires environment with sufficient DO, suitable pH and temperature, and the presence of the specific bacteria colonies. As shown in Table 6, effluent collected from A1 had higher DO concentration than that of effluent from A2. At SLR of 100 kg TS/m^2.yr, the wetland was relatively more aerated with thinner sludge residuals retained on top of the bed that dried out more rapidly and thus promoting oxygen diffusion into the substrata and increase the septage infiltration time.

TABLE 6

In situ test readings on effluent for wetland A1 and A2

	DO (mg/l)	Temperature (°C)	pH	Electric Conductivity (mS/cm)
A1 (SLR 100)	3.24	28.2	7.12	2.33
A2 (SLR 250)	2.40	28.3	7.25	1.95

Both wetlands produced effluents with increased DO from an average of 0.13 mg/l in the raw septage to 3.24 and 2.40 mg/l for A1 and A2, respectively. This indicates that our vertical-flow beds with weekly batch feeding performs aerobically, which is important for an efficient aerobic degradation of the oxygen consuming substances delivered with influent septage. The ventilation tubes placed in the substrate could also be a factor that helps support bottom ventilation to allow for oxygen diffusion through the substrate layers that is colonized by plant roots and nitrifying biomass, which could increase nitrification rate. Other authors have also highlighted the importance of oxygen concentration in EWs (see Cooper, 2005; Green *et al*. 2008; Noorvee *et al*., 2005). Good oxygen conditions favor nitrification and limit denitrification. Accordingly, total nitrogen removal in both the wetlands with SLR 100 and 250 did not differ significantly. From the experimental results, it was evident that SLR can affect ammonia removal and nitrate concentration in the system, with lower SLR achieving higher ammonia removal efficiency in a relatively more aerobic environment in the substrate.

Bed Clogging Assessment

Fig.2 depicts the solid retained on the bed surface 3 days after septage feeding onto the wetland and Fig.3 pictures the dried septage layer on the 8th day after sludge application, both with SLR of 250 kg TS/m^2.yr. Although wetland A2 was loaded with 250 kg TS/m^2.yr of SLR, which has 2.5 times higher the volume of septage applied per each batch, there was no bed clogging observed as evidenced from the draining efficiency of the septage during the course of operation of 8 weeks. Continuous growth of *phragmites* roots and rhizomes in the septage layers and the filter media, besides movement of plant stems helped to create airway into the beds and thus prevented media clogging. The beds remained aerobic with the applied load and feeding regime, as evidenced from the resulting effluent DO concentartion (Table 6). The preservation of aerobic conditions in the wetland substrate is the vital requisite for clogging prevention, besides effective nitrification (Platzer & Mauch, 1997). Quantification and qualification of the dried sludge layers are still afoot and the output is not presented in this paper.

Fig.2. Septage residual retained on top of the wetland A2 3 days after feeding with SLR 250 kg/m^2.yr

Fig.3. Dried septage residual retained on top of the wetland A2 after 7 days (SLR 250 kg/m^2.yr)

CONCLUSION

A specially-designed, two-staged, engineered wetland-based treatment system for septage was constructed, tested, and presented in this paper. Based on the results obtained from the preliminary experiment conducted for 8 weeks, the first stage of the septage treatment by the pilot VFEWs system was efficient, with ≥ 80% of removal for COD, BOD, NH3-N, and TS at solid loading of 100 kg TS/m^2.yr. It was shown that even with higher SLR at 250 kg TS/

m^2.yr, the wetland could still achieve similar removal with no statistically different treatment efficiency for most of the parameters tested except for NH_3-N. The overall performance of the wetlands is encouraging and prolonged and extended studies are still on-going to assess on how both various system and application-related parameters could affect the treatment efficiency of this system.

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