Treatment of septage in constructed wetlands in tropical climate: lessons learnt from seven years of operation

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Abstract In tropical regions, where most of the developing countries are located, septic tanks and other onsite sanitation systems are the predominant form of storage and pre-treatment of excreta and wastewater, generating septage and other types of sludges. The septage is disposed of untreated, mainly due to lack of affordable treatment options. This study presents lessons that have been learned from the operation of pilot-scale constructed wetlands (CWs) for septage treatment since 1997. The experiments have been conducted by using three CW units planted with narrow-leave cattails (*Typha augustifolia*) and operating in a vertical-flow mode. Based on the experimental results, it can be suggested that the optimum solids loading rate be 250 kg TS/m^2 yr and 6-day percolate impoundment. At these operational conditions, the removal efficiencies of CW units treating septage at the range of 80–96% for COD, TS and TKN were achieved. The biosolid accumulated on the CW units to a depth of 80 cm has never been removed during 7 years of operation, but bed permeability remained unimpaired. The biosolid contains viable helminth eggs below critical limit of sludge quality standards for agricultural use. Subject to local conditions, the suggested operational criteria should be reassessed at the full-scale implementation.

Keywords Nutrient removal; operation; helminth eggs; septage treatment; vertical-flow constructed wetlands

Introduction

Discharging untreated septage, the material accumulating in onsite sanitation systems, into watercourses or land may cause environmental degradation and serious public health risks (Strauss *et al.*, 1997). Contrary to wastewater collection and treatment, the technological development in septage management has received little attention, resulting in the lack of affordable and technically appropriate treatment options in economically less developed areas and countries. Technologies used for septage treatment in industrialized countries include activated sludge or physiochemical dewatering processes, usually in conjunction with wastewater treatment. Yet, their application in developing countries is limited due to high construction and operational costs and lack of skills. The challenge this poses consists in devising septage treatment options comprising low-cost and simple-to-operate technologies while guaranteeing satisfactory performance.

A natural treatment system, convenient for treatment or dewatering of septage, is the vertical-flow constructed Wetland. They make use of the interactions of emergent plants and microorganisms in removing pollutants. Contrary to horizontal-flow CW systems, a vertical-flow CW unit forces the flow downwards through the filtering media to the drainage system. The alleged advantage of CWs over conventional sludge drying beds is the much lower frequency of dewatered sludge removal from the bed, allowing for several years of sludge accumulation prior to bed emptying. The possible mechanisms is likely due to the plant root and rhizome systems assisting in maintaining the permeating structure of the accumulating biosolids and providing channels to improve the drainage of percolate. Evapotranspiration of the emergent plants in CW units can result in better sludge dewatering. In addition, the retention time of the percolate within the accumulated biosolids and the filtering media, which is longer than in unplanted beds, enables nitrification/-denitrification reactions.

Septage treatment in CW units was first conducted at laboratory-scale at Cemagref in Lyon, France (Liénard and Payrastre, 1996), showing promising treatment performance and ease of operations. The Swiss Federal Institute for Environmental (EAWAG) and The Asian Institute of Technology (AIT) have jointly been undertaking field research to determine treatment efficiencies and to establish design and operational guidelines of the pilot-scale CW units treating septage in tropical conditions since 1996. This article reports about the lessons learnt from 7 years of investigations on the pilot-scale CW units.

Methods

Experimental setup

Size and configurations. Three pilot-scale CW units with square surfaces (5×5 m) were established at the Environmental Research Station of AIT. Each unit was constructed with ferro-cement walls and reinforced concrete slabs at the bottom (Figure 1).

Substrata and vegetation. Narrow-leaf cattails (*Typha augustifolia*), an indigenous species in Thailand, were planted at densities of 10–15 shoots/m^2 by transplanting from natural wetlands at the AIT campus. According to the suggestions given by Cooper *et al.*, (1996), the substrata of vertical-flow CW units planted with reeds should have a depth of 80 cm with 70 cm of graded gravel layers and topped off with 10-cm sharp sand. As the length of cattail roots is only about 30–40 cm, i.e. shorter than that of reeds with 50–60 cm, the substrata depth in these experiments was designed to be 65-cm, consisting of a 10 cm layer of 1-mm Ø fine sand, a 15 cm layer of 25-cm Ø small gravel, and a 40 cm layer of 50-cm Ø large gravel. A free board of 1 m was allowed for accumulation of the dewatered septage (biosolids).

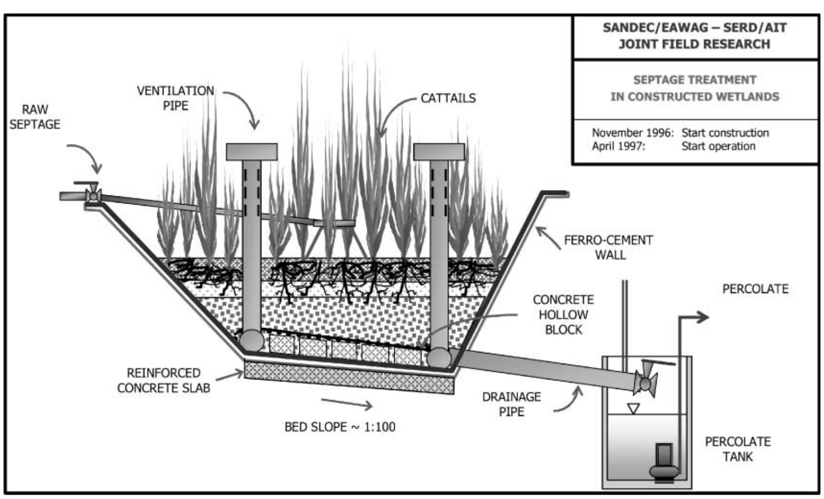

Figure 1 Schematic diagram of the AIT pilot-scale CW beds

Ventilation and drainage systems. The hollow concrete blocks with the dimensions of $20 \times 40 \times 16$ cm (width × length × hollow space) and perforated PVC pipes with a diameter of 20-cm are placed at the bottom. Mounted on the drainage system are ventilation pipes of the same diameter and extending approximately 1 m over the top edge of the units (as shown in Figure 1). Natural draught ventilation was deemed necessary to avoid anaerobic conditions in the filtering media and, hence, plant damages. The percolate from the three CW units is collected in three separate tanks of 1 m diameter.

Operating conditions

Initially, the operating conditions were based on information reported in published literature, which, however, related mainly to CW bed treatment of WWTP sludges in temperate climates. In order to determine the optimum operating conditions of CW units suitable for tropical regions treating FS (septage in the particular case), the solids loading rate (SLR), the frequency of septage application, and percolate impounding period were varied as shown in Table 1. Due to the high variation in solids concentrations, maintaining a constant volumetric application rate, which is based on statistical average for the TS concentration in the raw septage, is more practical than operating at a constant SLR.

Results and discussions

Characteristics of Bangkok septage

Characteristics of raw septage collected from different locations of Bangkok metropolitan areas are summarized in Table 2. Typically, septage characteristics exhibit high variations in pollutant concentrations.

Overall performance

The treatment efficiencies of each pilot-scale CW unit treating septage at different SLR, application frequencies, and impounding periods are shown in Table 3. The CW unit 1 received average SLR of 300 kg TS/m^2 yr, as compared to 230 and 180 kg TS/m^2 yr for CW 2 and 3, respectively. Based on the experimental results obtained to date, the following removal efficiencies were attained in the percolating liquid of CW 1: TS: 74–86%; COD: 78–99%; TKN: 70–99%, and NH_3: 50–99%. According to statistical analyses of

Table 1 Operating conditions of pilot-scale CW units

Phase	SLR (kgTS/m^2 yr)			Percolate impounding*	Frequency of septage application	Period of operation
	CW-1	CW-2	CW-3			
1a	250	125	80	No	Once + twice-a-week	Apr. 97 – Dec. 97
1b	500	250	160	No	Once + twice-a-week	Dec. 97 – Jan. 98
2a$^+$	250^a	250^b	250^c	Yes	Once-a-week	Feb. 98 – May 98
2b$^+$	260^a	240^b	250^c	Yes	Once-a-week	Jul. 98 – Feb. 99
3a-1$^+$	250^a	220^b	250^c	Yes	Once-a-week	Mar. 99 – Aug. 99
3a-2$^+$	210^d	260^a	–	Yes	Once-a-week	Sep. 99 – May 00
3b$^+$	240^a	–	–	Yes	Once-a-week	Jun. 00 – Dec. 01
4$^+$	250^a	–	–	Yes	Once-a-week	Jan. 02 – May 03

*Percolate was retained 10–15 cm below dewatered septage layers in CW units using a gate valve fitted to the drain pipe

$^+$To ease operations, septage was loaded at a constant volumetric rate of 8 m^3/week from Phase 2b (since Jul. 98), resulting in varying SLR

^{a}Impounding period = 6 days; ^{b}impounding period = 2 days; ^{c}no impounding; ^{d}impounding period = 12 days. '–' = no information

Table 2 Characteristics of Bangkok septage samples*

Parameter	Average	Median	Minimum	Maximum	Standard deviation
ORP (mV)	−222	−223	−380	−90	17
pH	7.5	7.5	6.7	8.1	0.4
TS (mg/L)	15,350	15,000	2,202	67,200	11,700
TVS (mg/L)	11,150	11,050	848	52,362	9,370
SS (mg/L)	12,900	12,550	980	43,633	10,110
VSS (mg/L)	9,250	9,650	840	34,667	7,630
TCOD (mg/L)	15,700	14,500	1,108	76,075	14,900
BOD_5 (mg/L)	2,300	2,000	630	5,550	1,360
TKN (mg/L)	1,100	970	226	4,880	424
NH_3-N (mg/L)	415	370	60	1,200	123
NO_3-N (mg/L)	7	7	0.2	21	4
Helminth eggs (no./g of sample)	6	6	0	14	1

*Based on 256 raw septage samples taken from April 1997 to May 2003

the overall experimental data, the removal efficiencies of CW units 1 and 2 are not different from those of CW 3.

The CW units treating septage produce percolates with considerable NO_3 concentrations (Table 3) (Koottatep *et al.*, 2001). For instance, percolate NO_3 concentrations of up to 320 mg/L were observed in CW 2 during Phase 1b (Dec. 1997–Jan. 1998), whereas the lowest concentration, observed in Phase 3a-2 (Sep. 1999–May 2000) amounted to 15 mg/L. In spite of the increase in NO_3 concentrations, mass balances made across the entire system comprising the raw septage, the accumulated biosolids, the cattail plants, and the percolate showed a net loss of N, which can be ascribed to denitrification and to ammonia volatilization.

Varying the septage loading frequency between once- and twice-weekly showed insignificant effects on treatment performance but twice-weekly loading helped support the growth of cattails during operations without percolate impounding. To minimize the workload in septage feeding, the once-a-week application was considered preferable, as percolate impounding was introduced as a permanent measure and provided adequate moisture for the cattails and treatment performance was the same for once-weekly and twice-weekly septage loading.

Lessons learnt from 7-years of operation

Variation of SLR and application frequency. As discussed above, the variations of SLR in the different CW units did not significantly affect overall treatment performance within the range of SLR 80–250 kg TS/m^2 yr. However, operating CW 1 at 500 kg TS/m^2 yr showed substantial reductions in performance. In addition, it was noticed that such high SLR caused cattail wilting. At the SLR of 80–250 kg TS/m^2 yr, the following removals in the percolating liquid were observed: TS: 66–88%; TCOD: 78–99%; TKN: 82–99%, and NH_3-N: 40–98% (Table 3). Based on the parameter testing, it is suggested that the SLR for constructed wetlands treating septage should not exceed 250 kg TS/m^2 yr for the kind of septage treated in the pilot experiments under Bangkok-type climate. To ease operational practice, the septage has been fed at the constant volume at the rate of 8 m^3/day, which correspond to the SLR of 210–260 kg TS/m^2 yr. This operating condition at the constant volume loading rate of 8 m^3/day could also achieve the treatment efficiencies at the same magnitude of those obtained from a constant SLR.

Effects of percolate impounding. Based on the experimental results during Phase 2b to 3b (Table 4), it can be noticed that the percolate impounding in CW units could achieve

Table 3 Percolate contents and removal performances for solids, organics and nutrients in CWs+

CW unit	Phase no.	SLR, kg TS/m^{2}yr	Frequency, no./week	Parameter*, mg/L				
				TS	TCOD	TKN	NH_3	NO_3
Raw septage **				15,350	15,700	1,100	415	7
Percolate								
1	1a	250	1	3,250 (71)	300 (97)	45 (96)	32 (98)	180
	1a	250	2	3,150 (80)	100 (99)	6 (99)	5 (99)	260
	1b	500	2	3,842 (66)	2,185 (78)	254 (69)	191 (52)	180
	1b	500	1	5,068 (80)	1,422 (92)	153 (87)	106 (71)	180
	2a	250[a]	1	2,784 (82)	268 (97)	87 (88)	59 (81)	50
	2b	260[a]	1	2,600 (82)	320 (98)	106 (89)	80 (81)	40
	3a-1	250[a]	1	1,890 (88)	390 (98)	150 (84)	100 (66)	45
	3a-2	210[d]	1	2,910 (76)	268 (98)	85 (90)	56 (85)	15
	3b	240[a]	1	3,244 (74)	270 (98)	61 (94)	46 (91)	100
	4	250[a]	1	1,870 (86)	430 (97)	107 (88)	73 (80)	165
2	1a	125	1	2,310 (81)	250 (97)	57 (93)	56 (78)	180
	1a	125	2	2,780 (82)	280 (98)	62 (96)	44 (92)	190
	1b	250	2	3,679 (67)	826 (86)	137 (80)	101 (70)	320
	1b	250	1	5,796 (78)	1,053 (96)	119 (90)	95 (74)	230
	2a	250[b]	1	3,621 (72)	431 (97)	64 (90)	36 (87)	55
	2b	240[b]	1	2,700 (78)	450 (97)	150 (84)	11 (70)	55
	3a-1	220[b]	1	2,116 (83)	528 (96)	170 (82)	120 (64)	42
	3a-2	260[d]	1	3,886 (73)	349 (97)	56 (94)	30 (92)	42
3	1a	80	1	2,310 (80)	340 (97)	62 (93)	46 (84)	210
	1a	80	2	2,940 (81)	410 (97)	105 (94)	98 (85)	230
	1b	160	2	3,861 (69)	1,021 (88)	182 (78)	142 (62)	270
	1b	160	1	5,060 (82)	1,925 (94)	237 (82)	169 (52)	190
	2a	250[c]	1	3,641 (75)	1,369 (91)	162 (80)	96 (65)	100
	2b	250[c]	1	3,300 (76)	780 (94)	200 (79)	140 (60)	106
	3a-1	250[c]	1	2,410 (84)	1,025 (94)	270 (60)	184 (40)	135

*Average data were based on composite samples taken from each experiential phase

**Raw septage data was averages of 256 samples of Phase 1–4, during April 1997 to May 2003

+Removal efficiencies as shown in parentheses depended on the characteristics of raw septage used in each phase

[a]Percolate impounding of 6 days; [b]percolate impounding of 2 days, [c]no impounding; [d]percolate impounding of 12 days

Table 4 Treatment performances of CW units during Phase 2b to 3b+

Unit no.	Impounding periods, days	Parameters, mg/L					
		SS	**TS**	**TCOD**	**TKN**	**NH_3**	**NO_3**
Raw septage		**11,820**	**13,710**	**14,485**	**993**	**412**	**9**
Percolate							
1	12	147 (99)	3,886 (73)	349 (97)	56 (94)	30 (92)	13
1	6	111 (99)	3,112 (78)	289 (98)	90 (91)	62 (85)	36
2	2	228 (98)	2,557 (82)	459 (97)	139 (86)	99 (76)	50
3	0	391 (97)	3,035 (78)	803 (95)	198 (80)	140 (66)	106

+Averaged from 144 composite samples, while removal efficiencies are given in parentheses depended on the characteristics of raw septage

significant effect on N removal, rather than the removals of solid and organic matters. The low NO_3 concentrations were observed in the impounded percolates than in the non-impounded ones (Table 4). Impounding could likely lead to anaerobic conditions in the percolate and, hence, possibly allows denitrification reactions in the CW units. Impounding for 12 days resulted in the highest TKN and NH_3 removals (amounting to 94% and 92%, respectively), as well as in the lowest percolate NO_3 concentrations. Nevertheless, a 12-day impoundment is not compatible with a once-a-week septage loading practice. Therefore, a percolate impounding period of 6 days was finally chosen as the appropriate operation, still guaranteeing satisfactory removal efficiencies (TKN: 91% and NH_3: 85%). Moreover, average NO_3 concentrations in the CW percolate at the impounding period of 6 days was only 36 mg/L, as compared to 50 and 106 mg/L for the beds subjected to 2 and 0 days of impoundment, respectively. Percolate impounding had insignificant effects on TS and TCOD removal efficiencies, probably because the filtering capacity of the CWs remained unaffected and biodegradation of organic constituents was modest anyway. The effluent SS concentrations of the CW units at impounding periods of 6 and 12 days were slightly lower than those obtained from a 0 or 2-day impounding, likely due to the better settleability of suspended particles within the filter media.

Plant growth pattern and harvesting. The cattails were subjected to shock loading and water deficiency during the early stage of Phase 1a (Apr 97–Dec 97) but they could survive and grow well afterwards upon full acclimatization. The growth patterns of cattails were seriously hampered during the beginning of Phase 1b (Dec 97 to Jan 98). At the highest SLR of 500 kg/m^2 yr, the cattail plants appeared to be severely affected and required a relatively long period (1–2 month) to recover and become healthy again. At the beginning of Phase 2a (Feb 98 to May 98), the cattails were only 1.5–1.8 m in height, only. After acclimatization and 4 months of operations, the cattails in CW units were harvested at the height of 3.6–4.0 m, relatively high as compared to the cattail plants in the natural water body.

The cattails showed signs of wilting at the initial stage of operation with once-a-week loading and were shocked at SLR higher than 250 kg TS/m^2 yr. At twice-a-week application, the cattails grew slightly better because only half of the weekly septage load was loaded at each application. The cattail plants were adapted to septage and exhibited a healthy growth pattern even at once-a-week application after one year of operation.

To rejuvenate and maintain the CW effectiveness, the cattails should be harvested regularly when plants show wilting symptoms, i.e. when they have passed the culmination in their growth cycle, but do not need to remove dried septage (biosolids) in CW units during the plant harvesting. Dry biomass of the harvested aboveground portions of the cattails ranged from 3.0 to 5.4 kg/m^2 corresponding to net production rates of 43–76 ton/ha.yr.

Shading and unequal distribution of septage loading might cause reductions in plant density and impair the growth of young shoots. Temporary water scarcity can result in the decrease of plant density also. The harvesting of cattails at the end of their growth cycles had negligible impact on the performance of the CW units, but it proved essential in getting rid of the invasion of weeds.

Hygienic quality and fertilizing value of the accumulated biosolids

Helminth eggs, which constitute the hygiene criteria-of-choice for biosolids reuse, become concentrated in on-site sanitation systems and, hence, during septage treatment in CW units. Table 5 shows the numbers of helminth eggs in the deeper (45 cm from surface) and upper layer (15 cm from surface) of the accumulated biosolids in CW1 as observed during Phase 3b and 4 monitoring. The egg concentrations in CW1 were higher in the upper than in the lower layer, possibly due to the fact that many of the eggs in the deeper layer might have been completely disintegrated during the several years of solids storage. In contrast to this, the numbers of helminth eggs in the upper layer of the biosolids accumulated in CW 2, which did not receive septage during 1.5 years preceding sampling, were found to be lower than those in the deeper layer. This might be due to the fact that eggs contained in the upper layer were subjected to solids drying more intensively than those in the deeper zone. Egg viability in all biosolid samples was less than 10%, resulting in absolute viable egg concentrations of <6 eggs/g TS. This can be considered safe for agricultural use against the tolerance limit of 3–8 eggs/g TS as proposed by Xanthoulis and Strauss (1991), which is derived from the WHO wastewater reuse guideline of <1 nematode egg/L for unrestricted irrigation (WHO, 1989) and based on a manuring rate of 2–3 tons TS/ha·year.

Sludge accumulation

The solids accumulation rate amounted to 12 cm per year, resulting in an 80-cm sludge layer after seven years of continuous septage loading. Given the freeboard of 1.0 m chosen for the AIT pilot plant, solids accumulation is likely to last for about a total of 10 years before emptying becomes necessary. In spite of this extended loading without removal of accumulated biosolids, there has been no bed clogging and percolate flow remained entirely unimpeded. This phenomenon was presumably due to the continuous growth and distribution of the cattail roots and rhizomes as well as to the conservation of dead roots in the accumulated solids layers, which helped create and maintain porosity in the CW beds.

CWs built based on the lesson learnt

Based on the lessons learnt and operational guidelines achieved from this study, demonstration CW units have been installed at Baanklang sub-district in Lamphoon Province, Thailand in order to treat septage at the capacity of 1,000 m^3 of septage per year as from Jan. 2004. The demonstration units consists of 2 CW units receiving raw septage and two CW units treating percolate of the former CW units, occupying a total area of 900 m^2 (300 m^2 for irrigation area by treated percolate). Each CW unit has a surface of 5×5 m

Table 5 Number of helminth eggs in the Phase 3b and 4 monitoring campaigns

Layer	Unit	CW 1**	CW 1*	CW 2*
Upper (15 cm from surface)	Eggs/g of TS	80	127	97
Deeper (45 cm from surface)	Eggs/g of TS	40	33	144

*Average from 12 samples from CW 1 and CW 2 in Phase 4, and **Average data of Phase 3b with a substrata depth of 65 cm and a freeboard of 1 m. It is expected that the design criteria and operating conditions can be tested and verified based on continuous opera tions and monitoring of the plant. A full-scale CW plant designated to treat septage was also installed in the town of Nam Dinh in Northern Vietnam, in anticipation of commissioning.

Conclusions

Uncontrolled septage management endangering public health and the environment calls for effective management strategies with an appropriate treatment option that is properly designed and operated. The 7-year experimental results of the cattail-planted CW units treating septage suggest that the optimum operating conditions include SLR of 250 kg TS/m^2 yr or constant volume loading of 8 m^3/week, once-a-week application and percolate impounding periods of 6 days with plant harvesting of twice a year. The percolate impounding in CW units is an essential operating condition to avoid plant wilting as well as to significantly enhance nitrification/denitrification reactions that lead to a lowering of nitrogen loads in the percolate. By maintaining the accumulated biosolid layers for several years, it can help reduce the numbers of viable helminth eggs and prevent its distribution into the environment, if reuse is undertaken. The results generated to date indicate that vertical-flow CW units constitute a promising, modest-cost technology for treating septage.

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