POTENTIALS OF VERTICAL-FLOW CONSTRUCTED WETLANDS FOR SEPTAGE TREATMENT IN TROPICAL REGIONS

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ABSTRACT

Constructed wetlands (CWs) have been proven to be an effective low-cost treatment system, which utilizes the interactions of emergent plants and microorganisms in the removal of pollutants. For wastewater treatment, CWs are typically designed to operate in either free-water surface or subsurface flow hydraulic patterns, while a vertical-flow operation is used to treat sludge or septage having high solid contents. This paper presents an assessment of the potentials of vertical-flow CWs for septage treatment in tropical regions where microbial reactions and plant growth rates are substantially high.

This study was conducted at the Environmental Research Station of AIT, using three pilot-scale CW beds, each with a dimension of 5 x 5 m^2. The CW beds consist of 65-cm sand-gravel substrata, supported by ventilated-drainage system and planting with narrow-leave cattails (*Typha augustifolia*). During the first year of operation, the CWs were operated at the solid loading rates (SLR) and application frequencies of 80 – 500 kg total solid (TS)/m^2.yr and 1 – 2 times weekly, respectively. The SLR of 250 kg TS/m^2.yr was found to result in the optimum treatment performances with respect to the TS, total chemical oxygen demand (TCOD) and total Kjeldahl nitrogen (TKN) removal efficiencies of 80, 96 and 92%, respectively, as well as less adverse effect on plant growth. At relatively high TS contents in the dewatered septage without any removal for a year, but permeability of the CW beds rarely decreased, probably due to the distribution of plant roots and rhizomes. It was also evident that there were high degrees of nitrification occurring in the CW beds in which the percolate had nitrate (NO_3^-) concentrations of 120 – 250 mg/L, while NO_3 contents in the raw septage were less than 10 mg/L. However, due to rapid flow-through of the percolates, there was little liquid retained in the CW beds, causing the cattail plants to wilt, especially during the dry season. In order for cattail plants to grow healthier, the operating conditions in the second year were rectified by ponding (or retaining) the percolate in the CW beds for periods of 2 and 6 days prior to discharge, but maintained the SLR of 250 kg TS/m^2.yr. This operating condition was obviously beneficial not only for mitigating plant wilting but also for increasing N removal through enhanced denitrification reactions in the CW beds, resulting in the percolate NO_3 concentrations of 20 – 50 mg/L. Apart from the treatment performances, land requirement of the vertical-flow CWs was estimated to be only 32.5 m^2/1,000 capita with the low capital, operation and maintenance costs. The vertical-flow CW systems thus have a high potential for septage treatment in tropical regions where land areas are available.

KEYWORDS

Cattails; constructed wetlands; nitrification; denitrification; operating strategies; septage; vertical-flow.

LIST OF ABBREVIATIONS

BOD	= Biochemical oxygen demand	SLR	= Solid loading rate
CW	= Constructed wetland	TCOD	= Total chemical oxygen demand
N	= Nitrogen	TKN	= Total Kjeldahl nitrogen
NH_4	= Ammonium	TS	= Total solids
NO_3	= Nitrate	TVS	= Total volatile solid

1. INTRODUCTION

CWs are man-made systems aiming at simulating the treatment processes in natural wetlands by cultivating emergent plants e.g. reeds (*Phragmites*), bulrushes (*Scirpus*), and cattails (*Typha*) on sand, gravel, or soil media. Based on investigations of pilot and field-scale systems, CWs have been proven to be a promising treatment alternative characterized by low investment, operation and maintenance costs (Kadlec and Kngiht, 1995 and Cooper *et al*., 1996). Therefore, utilization of CWs in waste treatment and recycling is currently of interest, including their ancillary benefits such as supporting primary production and enhancement of wildlife habitats. For several years, a number of CW systems have been employed to treat various kinds of wastewaters including, more recently, sludge from conventional treatment plants (Heinss and Koottatep, 1998).

For sludge or septage dewatering, a vertical-flow mode of operation with a percolate-drainage system beneath CW beds is required. An advantage of CWs over conventional, unplanted 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. Furthermore, the percolating liquid is subjected to microbial reactions within the CW beds, enabling nitrification and higher removal efficiencies within the liquid. Septage treatment in CWs was conducted in laboratory-scale experimental units at Cemagref in Lyon, France (Liénard and Payrastre, 1996), showing the promising treatment performance and ease of operations. Since 1996, the EAWAG and AIT have jointly undertaken research collaboration on “Septage Treatment by CWs and Attached-growth Waste Stabilisation Ponds” to test the feasibility of this treatment option and to establish design and operational guidelines. This article presents the 2-year experimental results of the CWs employed to dewater septage. Economic appraisal on the CW systems has also conducted to determine investment and operation costs suitable for developing countries.

2. MATERIALS AND METHODS

2.1 Experimental Setup

Configurations and Dimensions - Based on the site and literature surveys of the CWs treating sludge in Europe (Heinss and Koottatep, 1998), it was evident that performances of these CW units were not dependent of length to width ratio, but more on distribution of sludge onto the bed surface. The AIT pilot-scale CWS were then figured to be square in shape in order that septage could be uniformly distributed by a feeding system. The AIT CWs comprise of three vertical-flow units, each with a surface area of 5 x 5 m and lined with ferro-cement as shown in Fig. 1.

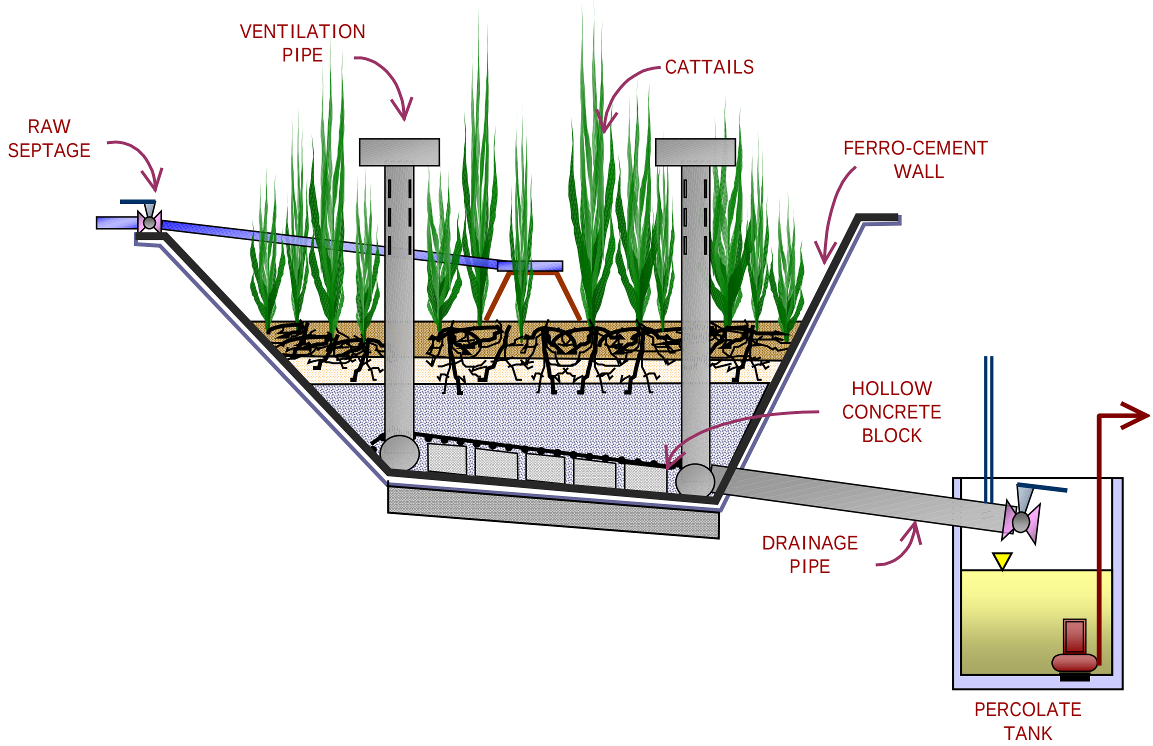

Figure 1. Schematic diagram of pilot-scale CW units

Filter Media and Vegetation - Based on the suggestions of Cooper *et al*. (1996), the filter media of CW units planting with reeds should have a depth of 80 cm with a 70-cm graded gravel layer and topped off with 10-cm coarse sand. Because length of the cattail roots is only about 30-40 cm, relatively shorter than reeds (50-60 cm), the substrata depth in these experiments was designed to be 65 cm. A 10-cm layer of fine sand, 15-cm layer of small gravel, and 40-cm layer of large gravel from top to bottom were used as substrata in each CW unit. A free board of 1 m was allowed for accumulation of the dewatered septage. On top of the sand layer, narrow-leave cattails (Typha augustifolia), collected from a nearby natural wetland, were planted in each CW unit at the initial density of 40-50 shoots/m^2. Cattails were selected because they are indigenous species and evidently growing better than reeds in most wetland areas of Thailand.

Ventilation and Percolation Systems - The bed support and drainage system consist of hollow concrete blocks, each with a dimension of 20 x 40 x 16 cm (width x length x hollow space), and perforated PVC pipes with a diameter of 20 cm at the bottom. Mounted on the drainage system are ventilation pipes of the same diameter and extending approximately 1 m over top edge of the units. Natural draught ventilation is required to avoid anaerobic conditions in the root zone and, hence, plant damage. The percolate of each CW unit was collected in a 3-m^3 concrete tank for sampling and analysis.

2.2 Operating Conditions

Cooper *et al.* (1996) suggested solid loading rates (SLR) for reed beds treating excess sludge from a wastewater treatment plant in Europe to range from 30 – 80 kg total solids (TS)/m^2.yr and sludge loading frequency should be once a week. In tropical regions, it is expected that CWs could be loaded at the higher ranges of SLR.

Septage used in these experiments was transported from Bangkok city. To remove garbage and rags, the raw septage was passed through bar screen and then homogenized in two 4-m^3 mixing tanks before feeding to the CW units. The CW units were subjected to the operating conditions as shown in Table 1.

Table 1
Operating conditions of pilot-scale CW units

Run	SLR (kgTS/m^2.yr)			Percolate	Frequency of	Periods of
	CW-1	CW-2	CW-3	ponding *	Septage application	Operation
I	250	125	80	No	twice-a-week	Apr. 97 – May 97
II	250	125	80	No	once-a week	May 97 – Jul. 97
III	250	125	80	No	twice-a-week	Aug. 97 – Dec. 97
IV	500	250	160	No	twice-a-week	Dec. 97 – Jan. 98
V	500	250	160	No	once-a week	Feb. 98 – Mar. 98
VI	250[a]	250[b]	250[c]	Yes	once-a week	Apr. 97 – Feb. 99
VII[+]	140 – 360	140 – 360	140 – 360	Yes	once-a week	Mar. 99 – Sep. 99

* Percolate was retained 10 –15 cm below dewatered septage layers in CW units
[+] To ease the operational practices, septage was loaded at the constant volume of 8 m^3/week, resulting in variations of SLR
[a] ponding period = 6 days, [b] ponding period = 2 days, [c] no ponding

In Runs I – V, the CW percolates were allowed to flow freely into the percolate tanks soon after septage feeding. For Run VI, the percolate ponding conditions were maintained by closing the outlet valves according to the designed ponding periods. In stead of maintain the constant SLR, which would result in variations of volume loading, the septage was loaded at the constant volume of 8 m^3/week, corresponding to SLR range of 140 – 360 kg TS/m^2.yr in Run VI, which aims to ease the operational practices of CWs.

Samples collected from the CW units at different operating conditions were analyzed for the contents of TS, total volatile solids (TVS), suspended solids (SS), biochemical oxygen demand (BOD), TCOD, TKN, ammonium (NH_4), NO_3, and helminth eggs. Analytical methods for these parameters were according to Standard Methods for the Examination of Water and Wastewater (APHA, AWWA, WPCF, 1992).

3. RESULTS AND DISCUSSION

3.1 Characteristics of Bangkok Septage

During the 2-year observations, the Bangkok septage showed the characteristics as given in Table 2, based on septage samples during August 1997 – September 1999.

Table 2
Characteristics of Bangkok septage samples

Parameter	Range	Average	Standard deviation
pH	6.7 – 8.0	7.5	0.6
TS (mg/L)	5,700 – 28,000	16,400	6,000
TVS (mg/L)	4,000 – 21,800	12,170	4,600
SS (mg/L)	3,150 – 21,600	13,600	5,800
BOD (mg/L)	600 – 5,500	2,800	1,400
TCOD (mg/L)	5,400 – 34,500	18,200	7,600
TKN (mg/L)	370 – 1,500	1,060	360
NH_4 (mg/L)	200– 590	390	110
NO_3 (mg/L)	8 – 20	12	3
Helminth eggs, no./g of sample	0 – 14	5	1

The Bangkok septage had solid and organic contents in the same ranges as those reported by U.S. EPA (1995), but having relatively higher N contents. The low ratio of BOD to TCOD concentrations in the Bangkok septage showed the biodegradable fractions were mostly decomposed in the septic tanks. Because public hygiene and sanitation in Thailand, especially in the capital city, have significantly improved, the numbers of helminth eggs in the septage samples were evidently lower than those observed in other developing countries. Therefore, the Bangkok septage could be classified as type "B" or low-strength fecal sludge as suggested by Strauss *et al.* (1997).

3.2 First-year Results: Run I – IV Experiments

The results obtained from the first year operation during Run I – IV showed that removal efficiencies of TS, TCOD, TKN, and NH_4 to be mostly higher than 80%, while the average NO_3 concentrations increased from 8 to 180 – 260 mg/L (Table 3). Analyses of the CW performance are given below.

Table 3
Average TS, TCOD, TKN, NH_4, and NO_3 contents in CW percolate and removal [+]

Sample	Run	Unit No.	SLR kg TS/m^2.yr	Frequency No./week	Parameter [*], mg/L: TS	TCOD	TKN	NH_4	NO_3
Raw septage[**]					16,300	16,000	830	340	8
Percolate	I	1	250	2	3,340 (81)	810 (97)	110 (95)	100 (90)	260
		2	125	2	3,610 (80)	570 (96)	62 (98)	44 (93)	190
		3	80	2	2,980 (83)	110 (98)	10 (99)	5 (98)	200
	II	1	250	1	2,640 (80)	300 (97)	62 (93)	46 (85)	180
		2	125	1	2,840 (80)	230 (98)	60 (96)	56 (80)	180
		3	80	1	3,640 (78)	210 (98)	45 (98)	32 (92)	210
	III	1	250	2	2,720 (88)	780 (95)	110 (94)	87 (88)	200
		2	125	2	2,700 (84)	460 (97)	100 (96)	36 (91)	190
		3	80	2	2,670 (86)	910 (94)	95 (99)	49 (79)	260
	IV	1	500	2	2,900 (81)	1,020 (93)	182 (87)	190 (69)	180
		2	250	2	3,600 (76)	800 (94)	140 (90)	100 (79)	220
		3	160	2	3,800 (80)	1,720 (88)	250 (79)	190 (52)	190

[+] Removal efficiencies as shown in parentheses depended on the characteristics of raw septage used in each experimental run.
[*] Average data were based on 12 composite samples taken from each experimental run.
[**] Raw septage data were averages of 72 samples of Run I to IV, during April 1997 – January 1998.

Solid Removal and Sludge Drying - Based on the results of Runs I – III, which had the same ranges of SLR, the frequencies of septage application did not have significantly effects on the TS removal efficiencies. The TS removal efficiencies achieved in the CW beds were similar to those of the sand drying beds treating the septage, which were experimented in parallel for comparisons (Pinsakul, 1997; Limsuwan, 1997). At the end of the 4-month operation of Run II, the TS contents of the dewatered septage increased from 1 – 2% to 30 – 60% after about one week of dewatering. It was also observed that average heights of the dewatered septage layers were 1.5, 2.3 and 5.0 cm in the CW units operated at the SLRs of 80, 125 and 250 kgTS/m^2.yr, respectively.

From statistical analyses, the treatment efficiencies of Run III were higher than Runs I and II, probably because of the accumulated dewatered septage layers which contribute to better filterability and increased microbial reactions. It was also apparent from the results of Run IV that further increases in SLR resulted in decreased CW performance in term of TS removal. The high SLR corresponded to the large volume of applied septage, which were beyond the filtration capacity of the CW beds, hence the lower TS removal efficiencies. However, as a result of the filtering capacity, no helminth egg was found in the percolate samples of the CW units (Limsuwan, 1997).

Organic Removal - During the first 8-month of Runs I – IV operations, the TCOD removal efficiencies ranged from 88 to 98%, resulting in the percolate TCOD concentrations of 210 – 1,720 mg/L (Table 3). Similar to the TS removal, the frequency of septage application did not have any significant effects on the TCOD removal efficiencies. It appeared that the TCOD removal depended on filtration capacity of the CW units rather than organic biodegradation at relatively short HRT. Another cause of the little biodegradation activity was the low biodegradability of the Bangkok septage, which had a BOD/COD ratio of 0.12.

N removal - Based on the results shown in Table 3, the TKN removal efficiencies of the CW units during Runs I – IV were mostly greater than 80% and having percolate TKN concentrations of 45 – 250 mg/L, while the NH_4 removal efficiencies were found in the range of 52 – 98%. The percolate NO_3 concentrations were increased significantly from 8 to 180 - 260 mg/L, probably because of the nitrification reactions. Moreover, the percolate DO concentrations of 2 – 4 mg/L supported the growth of the nitrifying bacteria. This result revealed the beneficial effects of the vertical-flow mode of operation and the ventilated-drainage system that enhanced the nitrification reactions.

Growth Patterns of Cattails - At the beginning of operation, the cattail plants in the CW units were 1.5-1.8 m in height. After two to three weeks of septage application, young roots and stems began to grow, but some cattail plants could not adapt to the septage, causing their leaves to turn yellow and died.

From observations, the cattail plants in the CW units showed a sign of water deficiency in Run I and were shocked during Run II, which was due to the once-a-week loading. From Run III, the plants could grow well because they became acclimated to the septage and septage loading was done twice a week.

After doubling the SLR to be 160, 250 and 500 kg/m^2.yr in Run IV, serious wilting symptoms and plant die-offs occurred in all CW units. The cattail plants in CW units no. 1 and 2 were manually harvested without removal of the dewatered septage layers, while no plant harvesting was implemented in unit no. 3.

3.3 Second-year Results: Run V – VII Experiments

At the end of Run IV, heights of the dewatered septage layers were increased to be 20 – 25 cm. The results obtained from the second year operation and beyond are shown in Table 4, and their analyses are given below.

Table 4
Average TS, TCOD, TKN, NH_4, and NO_3 contents in CW percolate and removal [+]

Sample	Run	Unit No.	SLR kg TS/m^2.yr	Ponding days	Parameter [*], mg/L TS	TCOD	TKN	NH_4	NO_3
Raw septage [**]					18,500	16,000	1,000	440	6
Percolate	V	1	500	-	4,960 (82)	1,880 (94)	240 (82)	170 (52)	250
		2	250	-	6,030 (77)	850 (96)	120 (87)	110 (70)	320
		3	160	-	4,320 (77)	1,250 (91)	150 (83)	110 (68)	270
	VI	1	250	6	2,000 (86)	270 (98)	100 (89)	80 (81)	20
		2	250	2	2,400 (84)	400 (97)	150 (85)	100 (77)	53
		3	250	0	2,700 (81)	620 (96)	200 (80)	140 (69)	120
	VII [++]	1	140 – 360	6	2,600 (82)	320 (98)	106 (89)	80 (81)	22
		2	140 – 360	2	2,700 (78)	450 (97)	150 (84)	100 (70)	55
		3	140 – 360	0	3,300 (76)	780 (94)	220 (79)	140 (60)	130

[+] Removal efficiencies as shown in parentheses depended on the characteristics of raw septage used in each experimental run.
[++] Solid loading at the constant volume of 8 m^3/week
[*] Average data were based on 15 composite samples taken from each experimental run.
[**] Raw septage data were averages of 60 samples of Run V - VII, during February 1998 – September 1999

Solid Removal and Mass Balance - After maintaining the doubled SLR and septage application at once-a-week in Run V, the TS removal efficiencies were in the same ranges of those obtained from Run IV, asserting that the TS removal of CWs is independent of the septage application frequency. However, based on the results of Runs I – V, it was found that the SLR of 250 kg TS/m^2.yr resulted in the highest TS removal efficiencies. At the end of Run V (300 days of operation), the TS mass balances in each CW bed were analyzed as shown in Table 5. The accumulated TS inputs to CW units 1, 2, and 3 were 187, 115 and 112 kg TS/m^2, respectively. The average TS mass in dewatered septage amounted to 38 – 52% of the TS inputs, while about 11 – 12% of the TS inputs were in the percolate portion. The unaccounted TS of 36 – 50% was postulated to be due to biochemical reactions such as mineralisation, biodegradation, and TS accumulation in the CWs substrata.

Table 5
TS mass balance in CW units after 300-day of operation

Balance	Unit no. 1 kg TS/m^2	Unit no. 1 %	Unit no. 2 kg TS/m^2	Unit no. 2 %	Unit no. 3 kg TS/m^2	Unit no. 3 %
Accumulated TS loading	187	-	115	-	112	-
Dewatered septage	93	50	60	52	43	38
Percolate	20	11	14	12	13	12
Unaccounted	74	39	41	36	56	50

The CWs operations in Run VI were maintained at the SLR of 250 kg TS/m^2.yr, while the CW percolates were withheld at the ponding periods of 6, 2 and 0 days in CW units 1, 2, and 3, respectively. It appeared from Table 4 that the percolate ponding periods did not have significant effects on the TS removal efficiencies, probably because the filtering capacity of the CWs did not increase via percolate ponding. In Run VII at the constant septage loading of 8 m^3/week corresponding to the SLR range of 140 – 360 kg TS/m^2.yr, it is apparent that no significant effect on the TS removal efficiencies in either CW units as compared to those resulted from Run VII. The CW units treating septage at this operating condition could, therefore, achieve the TS removal of 76 – 82%.

Organic Removal - The data of Run V confirmed that the SLR of 250 kg TS/m^2.yr yielded the highest TCOD removal of 96%. For Run VI and VII, the percolate ponding periods did not have any significant effects on the TCOD removal, similar to the TS removal efficiencies. It is postulated that sedimentation and filtration of organic particulate to be the major mechanisms responsible for TCOD removal in these CW units rather than biodegradation. The relatively low BOD/TCOD ratio of 0.1 – 0.2 in raw septage would likely be another cause of the scanty biodegradation.

N removal - The N removal efficiency of Run V at the SLR of 250 kg TS/m^2.yr was the highest. In Run VI, CW units 1 and 2 which had percolate ponding had higher TKN and NH_4 removal efficiencies than CW unit 3 without percolate ponding. This phenomenon was probably due to the denitrification reactions occurring in the CW beds. CW unit 1, having the longest ponding period of 6 days, achieved the highest TKN and NH_4 removal efficiencies, while the percolate NO_3 concentration was the lowest. The N plant uptake by cattail plants could be another N removal mechanism in the CW units, as reported by Kootatep and Polprasert (1997). However, because the relatively high N loading of septage employed in these experiments, the N plant uptake rates of these CW beds were accounted for only 5 – 7% of the total N input (Pinsakul, 1997). Based on the results obtained from Run VII, it is evident that the variation of SLR subjecting to the N loading did not cause any adverse effect on TKN and NH_4 removal. It was found that the CW units could have the TKN and NH_4 removal efficiencies of 79 – 89% and 60 – 81%, respectively, while the percolate NO_3 concentrations were 22, 55 and 130 mg/L in CW no. 1, 2 and 3.

Effects on Cattail Growth and Percolate Flow - Due to inadequate water availability, severe wilting of the cattail plants were observed in Run V as a result of the doubled SLR and once-a-week septage application. The wilted cattails in CW units 1 and 2 were harvested prior to the start-up of Run VI. With percolate ponding in Run VI and VII, the cattails in CW units no. 1 and 2 grew much better than those in CW unit no. 3, which, because of no plant harvesting, had interferences from other weeds and dead cattails.

Even when the dewatered septage layers in the CW beds were 45 – 60 cm in height at the end of Run VII and the dewatered septage was not removed from the CW beds, there was no bed clogging as evidenced from the percolate flows during the course of operation. This phenomenon was presumably due to the continuous growth and distribution of the cattail roots and rhizomes in the dewatered septage layers and substrata, which helped to create porosity in the CW beds. It is obvious that the practice of septage dewatering in vertical-flow CWs without frequent removal of the dewatered septage should result in significant reduction of operating costs, and confirming its advantage over conventional sand drying beds.

Economic Appraisal - In accordance with the pilot-scale CW operating experiences gained to date, a preliminary economic appraisal was conducted to determine the capital and annual O&M costs for septage treatment. The preliminary economic appraisal revealed the land-free capital costs could be amounted to 5,300 US$ for each of CW unit, incorporating soil excavations, wood piling, ferro-cement lining, filter materials, vent pipes, cattail cultivation, piping and percolation system, and concrete percolate tank. The annual O&M costs for septage loading, harvesting of cattails (once or twice a year), and cleansing of units is estimated to 500 US$/unit, excluding of the costs of dried sludge removal which may require after 4 – 5 years of operation. At the optimum SLR of 250 kg TS/m^2.yr, each CW unit is able to treat septage generated from about 1,000 capita, having daily septage generation rate of 1 L/person and TS content of 18 – 20 g/L (U.S. EPA, 1995). It could result in the capital and annual O&M costs of 5.3 and 0.5 US$/cap, respectively. In addition, the study suggested land requirement of the vertical-flow CW systems for septage treatment to be 32.5 m^2/1,000 persons.

4. CONCLUSIONS

Based on the 2-year experimental results, suitable strategies for the vertical-flow CW system treating septage were found to be: (i) SLR of 250 kg TS/m^2.yr or constant volume loading of 8 m^3/week; (ii) once-a-week septage application, and (iii) percolate ponding period of 6 days. These strategies resulted in optimum performance of CWs with respect to septage dewatering and contaminant removal from the percolating liquid, healthy and reliable plant growth, and ease of operations in which removal of the dewatered septage was not required. The percolate ponding significantly promoted the nitrification/denitrification reactions essential for N removal. Although more long-term data are required, the results generated to date indicated that the vertical-flow CW system is a promising technology for septage dewatering with low investment and operation costs.

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