SLUDGES FROM ON-SITE SANITATION SYSTEMS – LOW-COST TREATMENT ALTERNATIVES

Thammarat Koottatep*, Chongrak Polprasert*, Nguyen Thi Kim Oanh*, Agnes Montangero** and Martin Strauss**

* Urban Environmental Engineering and Management Program (UEEM),
School of Environment, Resources and Development (SERD)
Asian Institute of Technology (AIT), P.O. Box 4, Klong Laung, Pathumthani 12120, Thailand

** Department of Water and Sanitation in Developing Countries (SANDEC),
Swiss Federal Institute for Environmental Science and Technology (EAWAG)
P.O. Box 611, CH-8600 Dübendorf, Switzerland

Author to whom correspondence should be addressed: Thammarat Koottatep at thamarat@ait.ac.th

ABSTRACT

The majority of urban dwellers in Asia depend on on-site sanitation (OSS) systems for excreta disposal. There is, however, a considerable gap-in-knowledge on treatment options for faecal sludges evacuated from OSS, which are appropriate for developing countries. The authors provide an overview of options and describe in detail pilot-scale investigations on using constructed wetlands (CW) for the treatment of septage. The experiments are being conducted at AIT, Bangkok, since 1997. The plant consists of three beds planted with cattail (*Typha*). A loading rate of 250 kg $TS/m^2.yr$ and once-a-week sludge application were found optimum for the type of septage treated. Intermittent percolate impoundment is required to prevent cattail wilting during dry weather. TS, TCOD and TKN removals in the percolating liquid of 80, 96 and 92%, respectively, are achieved. 65 % of the septage liquid passes through the underdrain and 35 % is evapotranspirated. 60% of N is retained in the biosolids, with the remainder being "lost" in the percolate and by volatilization. The beds have been operated for nearly four years with unimpaired bed permeability. Accumulated solids contain ≤ 6 viable nematode eggs/g TS, thereby satisfying expedient sludge quality standards for agricultural use. Compared with conventional sludge drying beds, CW require a much lesser frequency at which dewatered biosolids need to be removed from the bed.

KEYWORDS

Cattails; constructed wetlands; faecal sludge treatment; septage; on-site sanitation

LIST OF ABBREVIATIONS

BOD	=	Biochemical oxygen demand	SLR	=	Solids loading rate
CW	=	Constructed wetlands	SS	=	Suspended solids
FS	=	Faecal sludge	TCOD	=	Total (unfiltered) chemical oxygen demand
N	=	Nitrogen	TKN	=	Total Kjeldahl nitrogen
NH_4	=	Ammonium	TS	=	Total solids
NO_3	=	Nitrate	TVS	=	Total volatile solids
OSS	=	On-site sanitation			

INTRODUCTION

Overview of Faecal Sludge Management

In urban areas of developing countries, on-site sanitation (OSS) systems predominate over water-borne, sewered sanitation. They comprise unsewered family and public toilets, aqua privies and septic tanks. In

Asia, 65 % of houses in large cities and up to 100 % in towns are served by on-site sanitation facilities. These will continue to play an important role for excreta disposal. In the USA, 25 % of dwellings are served by septic tanks. The collection of the faecal sludges from OSS installations and their haulage in large cities in Asia are faced with immense problems: difficult-to-access OSS facilities, traffic congestion, poorly-managed emptying services, long distances to designated disposal sites or treatment plants (if any). Therefore, most of the FS in developing countries are disposed of untreated and indiscriminately into lanes, drainage ditches, onto open urban spaces and into water bodies resulting in enormous health risks, water pollution and eye and nose sores. In some countries, FS is directly used in agriculture and aquaculture without any treatment.

Faecal Sludge Characteristics and Treatment Technology

Table 1 shows the values for the major constituents analysed in the septage, which was delivered to the constructed wetlands pilot plant operated at AIT, Bangkok. Most constituents are normally higher in FS by a factor of 10 or more compared with domestic, tropical wastewater. Moreover, FS differs from wastewater by the fact that its quality is subject to high variations, likely due to differences in storage duration, temperature, groundwater intrusion, and tank emptying technology and pattern. The anaerobic degradation process, which takes place in OSS systems and which is subject to differences in system design, retention period, and presence of inhibiting substances, might be a further cause for variation in FS characteristics. The range of values shown for Bangkok septage is typical of that for FS elsewhere. Helminthic infections are endemic in most developing countries. Hence, helminth eggs, which are shed in the excreta, accumulate in the faecal sludges. They are the most relevant hygiene quality parameter as it comes to agricultural use of FS. Fresh FS may contain from 4, -60,000 helminth eggs /L, tropical wastewater from a few hundred to 2,000 /L., depending on the endemicity and intensity of infection.

Table 1. Characteristics of Faecal Sludge and Sewage

Parameter	Range			Average		
	Faecal sludge		Sewage [c]	Faecal sludge		Sewage [c]
	Bangkok[a]	Europe [b]		Bangkok[a]	Europe [b]	
pH	6.7 – 8.0	5.2 – 9.0	-	7.5	-	-
TS (mg/L)	2,200 – 67,200	200 – 123,860	350 – 1,200	19,000	33,800	720
TVS (mg/L)	900 – 52,500	160 – 65,570	-	13,500	31,600	-
SS (mg/L)	1,000 – 44,000	5,000 – 70,920	200 – 700	15,000	45,000	220
BOD (mg/L)	600 – 5,500	700 – 25,000	110 – 400	2,800	8,343	220
TCOD (mg/L)	1,200 – 76,000	1,300 – 114,870	500 – 2,500	17,000	28,975	500
TKN (mg/L)	300 – 5,000	150 – 2,570	20 – 85	1,000	1,067	40
NH_4 (mg/L)	120 – 1,200	-	30 – 70	350	-	25

a. Based on 150 FS samples in this study during August 1997 – November 2000.
b. Adapted from Polprasert (1996)
c. Adapted from Metcalf and Eddy (1991)

Low-cost alternatives for FS treatment are shown in Fig. 1. The large land requirement of such options has to be carefully considered especially for urban areas where space is limited. Hence, semi-centralised treatment my often be the strategy-of-choice, requiring less land for individual plants and leading to shorter haulage distances than for centralised plants. Co-treatment with wastewater or sewage treatment plant sludge is expedient where such plants exist or are being planned and designed to receive the additional loads from FS.

A number of treatment alternatives comprise a preliminary solids/liquid separation step. This may be achieved in non-mechanised sedimentation tanks or ponds, or in drying beds. It allows to handle and treat separately the relatively large solids loads of FS, which constitute a valuable agricultural resource. While relatively high efficiencies in solids/liquid separation can be achieved in well-designed and operated separation units, concurrent organic and N removals are usually modest.

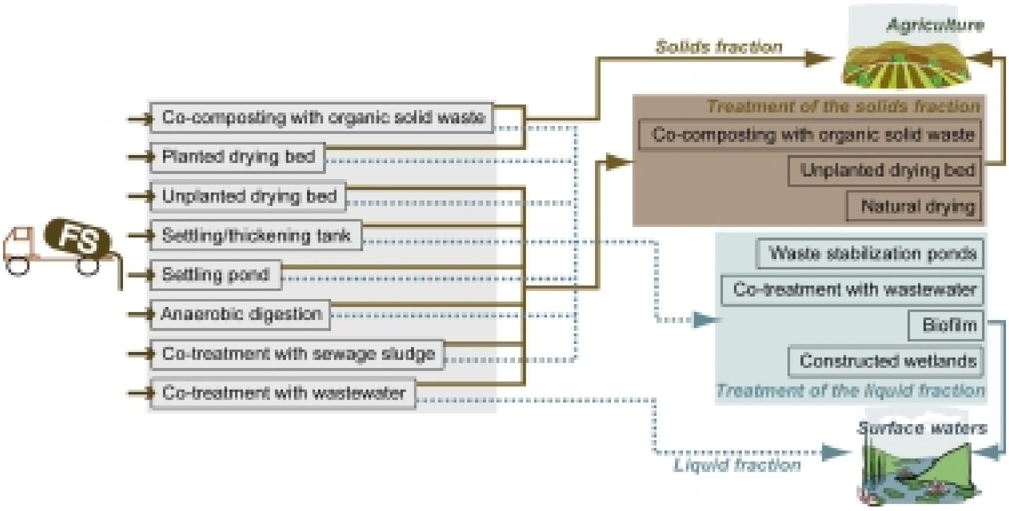

Fig. 1 Overview of potential, modest-cost treatment options for faecal sludge (Ingallinella *et al*., 2001)

Settling/thickening tanks and ponds require relatively frequent (few monthly to half yearly) removal of accumulated solids in order to maintain working volumes in the sedimentation units and to keep sludge volumes manageable.

Expedient treatment standards

In developing or newly industrialising countries, often unduly strict standards – at times uncritically copied from industrialised countries – are stipulated. They are usually neither enforceable nor enforced. Institutional, economic and political conditions are often not considered when formulating them. Hence, human wastes either remain untreated or treatment works, where existing, are not controlled. It should be recognised, that, in industrialised countries, treatment standards were made increasingly stringent in a process lasting for several decades, giving due consideration to the countries' evolving technical, economic and institutional capacities (Johnstone and Horan, 1996). Treatment options, which make use of modest and low-cost technologies and which may achieve some 70-80 % removals (as against 95-99% stipulated in industrialised countries), may already lead to very considerable reductions in health impacts and environmental pollution. As an example, Xanthoulis and Strauss (1991) proposed a guideline value for biosolids (as produced in faecal sludge or in wastewater treatment schemes) of 3-8 viable nematode eggs/ g TS. This recommendation is based on the WHO guideline of ≤ 1 nematode egg/L of treated wastewater used for vegetable irrigation (WHO, 1989), and on an average manuring rate of 2-3 tons TS/ha·year. For comparison, the standard to comply with in Western Europe, are 0 helminth eggs/g TS and ≤ 100 Enterobacteriaceae/g TS. This standard is extremely strict and can be attained through high-cost, sophisticated heat treatment (pasteurization) only. While such an option constitutes proven technology and is widely applied in industrialized countries, it is neither sustainable nor epidemiologically justified for the majority of economically less advanced countries.

CONSTRUCTED WETLANDS FOR SEPTAGE DEWATERING AND STABILIZATION – PILOT EXPERIMENTS AT AIT, BANGKOK

The process and preliminaries

In pursuing R+D for appropriate options of faecal sludge treatment, EAWAG/SANDEC has teamed up with AIT/UEEM to investigate upon the feasibility of using vertical-flow constructed wetlands (or planted sand drying beds) as a hypothetically feasible option.

CWs are man-made systems aiming at simulating the treatment processes in natural wetlands by cultivating emergent plants such as 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 feasible treatment alternative for wastewater and sludges from wastewater treatment plants characterized by low investment, operation and maintenance costs (Kadlec and Knight, 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 liquid wastes including, more recently, sludge from activated sludge treatment plants (Heinss and Koottatep, 1998).

For sludge 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 accumulating solids create a filtering matrix allowing for the development of attached-growth biomass. As a consequence, mineralisation processes are likely to lead to higher removal efficiencies than in unplanted sludge drying beds. Liénard and Payrastre (1996) of CEMAGREF in Lyon, France, have conducted pioneering laboratory-scale experiments using vertical-flow CW and reeds for treating septage. Their experience formed the basis for initiating the pilot investigations at AIT.

Experimental set-up

Dimensions. The AIT pilot-scale CWs are square-shaped to allow uniform distribution of raw septage. The pilot works comprise three vertical-flow units, each with a surface area of 5 x 5 m and lined with ferro-cement as shown in Fig. 2.

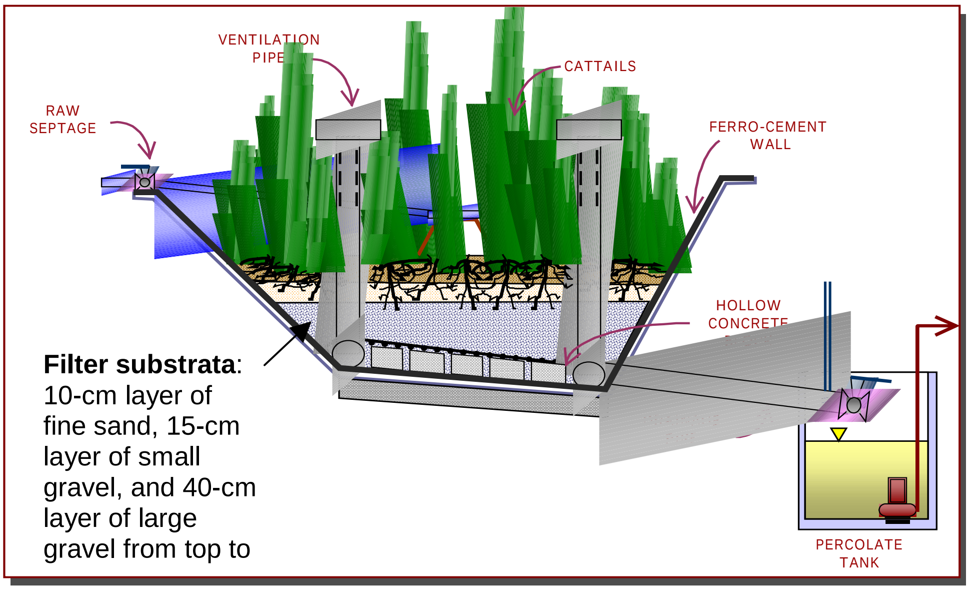

Fig. 2 Schematic diagram of a pilot-scale CW unit

Media Arrangement and Vegetation. The substrata depth in these experiments was designed to be 65 cm, because the length of the cattail roots and rhizomes is only 30-40 cm, as against 50-60 cm for reeds. 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 sludge. 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 8 shoots/m^2. The current density is 40-50 shoots/m^2. Cattails were selected because they are an indigenous species and evidently growing better than reeds in most wetland areas of Thailand.

Underdrain and Ventilation System. The bed support and drainage system consists 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.

Acclimatization

In order for cattails to acclimate with FS, AIT sewage was fed into the CW units at the application rate of 5 cm/d for about 2 – 3 weeks until the cattails had grown to 1.5-1.8 m in height. After that, FS was gradually fed into the CW units in combination with AIT sewage for about 2 months to minimize effects of ammonia toxicity towards the cattail plants. The young roots and stems of cattails began to grow, but some cattail plants could not adapt to the FS, causing their leaves to turn yellow and die. The CW units were then loaded with FS at the designed SLR and application frequency.

Operating Conditions

The authors hypothesized at the onset of the investigations that, in tropical regions, CWs can be loaded with FS at higher solids loading rates (SLR) than those experimented with by Cooper *et al.* (1996) in temperate climate. There, SLR ranged from 30 to 80 kg total solids (TS)/m^2.yr with once-a-week application.

For the study, septage was hauled from northern Bangkok by a contractual agreement. The raw FS was passed through a bar screen to remove coarse objects, and then homogenized in two 4-m^3 mixing tanks before feeding to the CW units. The CW beds were operated as shown in Table 2.

Table 2. Operating conditions of pilot-scale CW units

Run	SLR (kgTS/m^2.yr)			Percolate	Frequency of	Period of
	CW-1	CW-2	CW-3	ponding *	FS application	Operation
I	250	125	80	No	Once + twice-a-week	Apr. 97 – Dec. 97
II	500	250	160	No	Twice-a-week	Dec. 97 – Jan. 98
III	500	250	160	No	Once-a week	Feb. 98 – Mar. 98
IV	250[a]	250[b]	250[c]	Yes	Once-a week	Apr. 98 – Feb. 99
V[+]	140 – 360	140 – 360	140 – 360	Yes	Once-a week	Mar. 99 – Sep. 99
VI	175 – 450	-	-	Yes	Once-a week	Oct. 99 – Nov. 00

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

\+ To ease operations, FS was loaded at a constant volumetric rate of 8 and 10 m^3/week for Run V and VI, respectively, resulting in varying SLR

a Ponding period = 6 days, b ponding period = 2 days, c no ponding

In Runs I – III, the CW percolates were allowed to flow freely into the percolate tanks soon after FS feeding. As from Run IV, percolate ponding was introduced by closing the outlet valves for a selected number of days. In stead of maintaining a constant SLR, which would result in variations of the volumetric loading rate, FS was loaded at a constant volumetric rate of 8 m^3/week, allowing for easier control of loading operations. This corresponded with a SLR range of 140 – 360 kg TS/m^2.yr.

Samples collected from the CW units at different operating conditions were analyzed for total solids (TS), total volatile solids (TVS), suspended solids (SS), biochemical oxygen demand (BOD), TCOD (total, unfiltered COD), TKN, ammonium+ammonia (NH_4+NH_3), NO_3, and helminth eggs. Except for helminth eggs, analyses were performed based on Standard Methods for the Examination of Water and Wastewater (APHA, AWWA, WPCF, 1992). For helminth eggs, a method developed by USEPA and modified by Schwartzbrod (1998) was used.

Results and Discussion

*Variation of SLR and application frequency***.** The results obtained from Runs I – III (Table 3) show that at SLR ranging from 80 – 500 kg TS/m^2.yr, removal efficiencies for TS, TCOD, TKN, and NH_4, ranging from

Table 3. Average TS, TCOD, TKN, NH_4, and NO_3 contents in CW percolate and removal efficiencies during runs I-III+

Sample	Unit	SLR	Frequency	Parameter*, mg/L				
	No.	kg TS/m^2.yr	No./week	TS	TCOD	TKN	NH_4	NO_3
Raw FS**				16,300	16,000	830	340	8
Percolate	3	80	1	3,640 (78)	210 (98)	45 (98)	32 (92)	210
	2	125	1	2,840 (80)	230 (98)	60 (96)	56 (80)	180
	3	160	1	4,320 (77)	1,250 (91)	150 (83)	110 (68)	270
	2	250	1	6,030 (77)	850 (96)	120 (87)	110 (70)	320
	1	250	1	2,640 (80)	300 (97)	62 (93)	46 (85)	180
	1	500	1	4,960 (82)	1,880 (94)	240 (82)	170 (52)	250
Percolate	3	80	2	2,980 (83)	110 (98)	10 (99)	5 (98)	200
	3	80	2	2,670 (86)	910 (94)	95 (99)	49 (79)	260
	2	125	2	3,610 (80)	570 (96)	62 (98)	44 (93)	190
	2	125	2	2,700 (84)	460 (97)	100 (96)	36 (91)	190
	3	160	2	3,800 (80)	1,720 (88)	250 (79)	190 (52)	190
	1	250	2	3,340 (81)	810 (97)	110 (95)	100 (90)	260
	1	250	2	2,720 (88)	780 (95)	110 (94)	87 (88)	200
	2	250	2	3,600 (76)	800 (94)	140 (90)	100 (79)	220
	1	500	2	2,900 (81)	1,020 (93)	182 (87)	190 (69)	180

+ Removal efficiencies as shown in parentheses depended on the characteristics of raw FS used in each experimental run.

* Average data were based on composite samples taken from each experimental run.

** Raw FS data were averages of 72 samples of Run I to IV, during April 1997 – March 1998.

76 - 88 %; 88 - 98 %; 82 - 99 %, and 52 - 98%, respectively, were attained in the liquid percolating through the CW beds. As shown in Table 3, the application frequency of FS did not have significant effect on removal efficiencies at the same ranges of SLR. The average height of dewatered solids was 10 - 15 cm after one year of operation, exhibiting TS contents from 30-60 %.

Statistical analysis revealed that, similar to the application frequency parameter, the treatment efficiencies of the CW units did not depend on variations in SLR in the 80 – 500 kg TS/m^2.yr range. This may have been due to the considerable fluctuations in raw septage characteristics resulting in a wide range of effluent concentrations. Also, in the first two years of operation, the accumulated sludge layers were not high enough to lead to enhanced filtration effects. In addition, mineralisation of carbonaceous compounds within the filtering matrix was unlikely to play a significant role due to the relatively low biodegradability of Bangkok septage (COD:BOD ratio=6). Removal efficiencies decreased, though, upon doubling the SLR in each of the units.

TKN and (NH_4+NH_3) removals in the CW units are most likely caused by accumulation of organic-N in the dewatered sludge layers, mainly. Additional sinks for TKN and (NH_4+NH_3) are ammonia volatilization, plant uptake and nitrification reactions. It can be seen that NO_3 concentrations increased significantly from 8 mg/L in raw septage to 180 - 320 mg/L in the percolate due to aerobic conditions prevailing in the filter matrix and supporting nitrification. Dissolved oxygen concentrations of 2 – 4 mg/L in the percolate are evidence of an oxidative environment. The results reveal the beneficial effects of the vertical-flow mode and of drainage system ventilation, both enhancing nitrification.

It could be observed during the initial septage loading runs that the cattail plants in the CW units showed signs of wilting with once-a-week loading and were shocked at SLR higher than 250 kg TS/m^2.yr. At twice-a-week application, the cattail plants grew slightly better because only half of the weekly septage load was loaded at each FS application. The cattail plants were entirely adapted to FS and exhibited a healthy growth pattern even at once-a-week application after one year of operation. The results of the one-year parameter testing suggested that the optimum SLR is around 250 kg TS/m^2.yr and the frequency of application once-a-week for the type of septage delivered from northern Bangkok.

Variation of ponding periods

Inspite of the above results showing relatively high removals of TS, TCOD, TKN, and NH_4, the CW percolate remained relatively high in nitrate (NO_3). Also, the cattails showed signs of water deficiencies. In the experimental runs IV-VI, the percolate was therefore impounded in units no. 1 and 2 by gate valves for a specified number of days prior to discharge. The respective results are shown in Table 5.

Table 5. Average TS, TCOD, TKN, NH_4, and NO_3 contents in CW percolate and removal in runs IV-VI[+]

Sample	Unit No.	SLR kg TS/m^2.yr	Ponding days	Parameter[*], mg/L TS	TCOD	TKN	NH_4	NO_3
Raw FS[**]				18,500	16,000	1,000	440	6
Percolate	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
	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
	1	175 – 450	6	3,550 (72)	250 (98)	73 (92)	50 (89)	35

[+] Removal efficiencies as shown in parentheses depended on the characteristics of raw FS used in each experimental run.

[++] Solid loading at the constant volumetric loading rate of 8 m^3/week

[*] Average data were based on 15 composite samples taken from each experimental run.

[**] Raw FS data were averages of 60 samples during April 1998 – November 2000

The CWs were fed with septage at a solids loading rate of 250 kg TS/m^2.yr, while the CW percolates were withheld at ponding periods of 6, 2 and 0 days in CW units 1, 2, and 3, respectively. It appears from Table 5 that percolate ponding did not have significant effects on the TS and TCOD removal efficiencies, probably because the filtering capacity of the CWs remained unaffected by percolate ponding and degradation of organic constituents was modest. Removal efficiencies for TKN and NH_4 of 89% and 81% were attained, respectively with ponding period of 6 days. Moreover, average NO_3 concentration in the percolate was only 20 mg/L, as compared with 53 and 120 mg/L for the beds subjected to ponding of 2 and 0 days, respectively. This phenomenon was probably due to denitrification reactions occurring in the CW beds with a longer percolate ponding. Nitrogen uptake by cattail plants could be another N removal mechanism in the CW units, as reported by Koottatep and Polprasert (1997).

After the operating conditions were amended to a constant FS loading rate of 8 m^3/week (equivalent to a SLR ranging from 140 – 360 kg TS/m^2.yr), it became apparent that no significant difference in removal efficiencies of the CW beds occurred as compared to those fed at constant SLR. Hence, for reasons of operational easiness, the volumetric loading rate can be taken as the loading criteria, once the solids content of the particular septage has been ascertained with reasonable safety.

Solids accumulation and mass balances

70 cm of dewatered and stabilised solids had accumulated in the CW beds by the end of the 3.5 years experimental period, being equivalent to an average annual accumulation of 20 cm. Given the freeboard of 1.0 m chosen for the AIT pilot plant, solids accumulation is likely to last for at least a total of five years before emptying becomes necessary. The 70 cm of solids accumulated so far are equivalent to a septage column of 60 m loaded onto the beds. In spite of this extended loading without removal of accumulated solids, there was 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 in the dewatered sludge layers and substrata, which helped to create and maintain porosity in the CW beds.

At the end of Run V (300 days of operation), the TS mass balances in each CW bed were analyzed as shown in Table 4. 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 FS amounted to 38 – 52% of the TS inputs, while about 11 – 12% of the TS inputs were in the percolate portion. The unaccounted for TS of 36 – 50% can be attributed to the "loss" of organic matter through mineralisation to yield water and CO_2, and TS accumulation in the CWs substrata.

Table 4 TS mass balance in CW units after 1-year of operation

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

Fig. 3 is a graphical representation of the mass balances across the CW beds for nitrogen and water. N uptake by the cattails accounted for 5%, only, of the total N loaded through septage. N "losses" due to ammonia volatilization, microbial uptake and N accumulation in the CW support media, amount to some 10 – 30%, whereas nitrogen leaving the system in the percolate accounts for 10-25 %. Of the water brought onto the beds with septage, in the order of one third is evapotranspirated and two thirds are drained. Some 2 % only are retained in the accumulating solids.

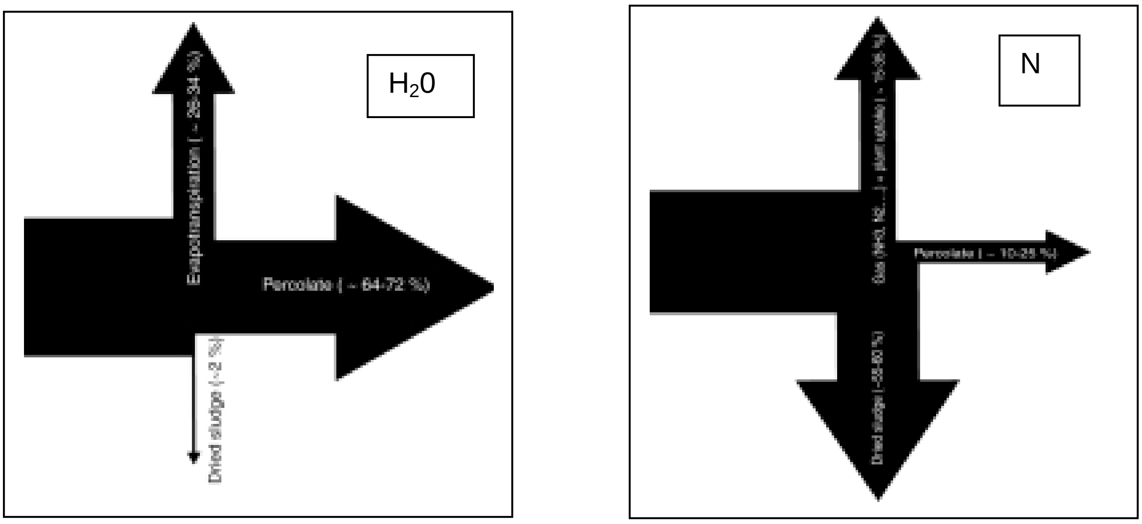

Fig. 3 Water and nitrogen balance in CW units fed with septage

Hygienic quality and fertilizing value of accumulated solids

Helminth eggs, which constitute the hygiene criteria-of-choice for biosolids earmarked for agricultural use, become concentrated in on-site sanitation systems and, hence, during further treatment in the filter body of constructed wetland beds. Nematode egg concentrations in the raw septage delivered to the AIT CW pilot plant ranged from 30-40 per g TS (495-660 /L of septage). This level is relatively low due probably to the limited endemicity and worm loads in the population from which the particular septage is collected. Nematode egg levels found in the dewatered and stabilised solids at the end of the reporting period, ranged from 100-270 per g TS, irrespective of the layer in the 70+ cm of accumulated solids. However, in none of the samples was the number of viable eggs higher than six (6) per g TS. The sludge is thus safe for agricultural use if measured against the expedient standard of 3-8 eggs per g TS as stipulated by Xanthoulis and Strauss (1991).

The nitrogen and phosphorus (as P) contents of the solids layer, which has accumulated during 3.5 years of septage loading, amounted to 3 % and 1.2 %, respectively. These compare very favourably with e.g. solid waste composts, due likely, to the fact that human excreta form the origin of the solids accumulating in the CW beds.

Costing appraisal

A preliminary financial appraisal was made to determine the capital and annual O&M costs for FS treatment through constructed wetlands based on the pilot-scale experiments. Land-free capital costs for the AIT pilot plant amounted to 5,300 US $ for each of the CW units. This comprises cost of soil excavation, wood piling, ferro-cement lining, filter materials, vent pipes, cattail cultivation, piping and percolation system, and concrete percolate receiving tank. Also included are auxiliary installations such as the receiving tank, bar screen and raw septage storage/mixing tanks (2 x 4 m3). Not included is the capital cost for percolate polishing (by e.g. stabilisation ponds). The annual O+M costs for FS loading, cattail harvesting (once to twice a year), and cleansing of units are estimated to amount to 500 US $/unit. This excludes costs for dewatered sludge removal, which will become necessary after a total of 5 years of operation, approximately. At the optimum SLR of 250 kg TS/m^2.yr, each CW unit is able to treat septage collected from about 1,000 persons based on a daily FS generation rate of 1 L/person and a TS content of 18 – 20 g/L (U.S. EPA, 1995). Thus, capital and annual O+M cost amount to 5.3 and 0.5 US $/cap, respectively. The gross land requirement (= net land requirement x 1.3) for the CW plant at AIT is equivalent to 32.5 m^2/1,000 persons. This excludes land required for percolate polishing, for which additional 7 m^2 /1,000 persons would be needed. Heinss et al. (1998) have calculated the area required for pond treatment of faecal sludges, inclusive of polishing and dewatering/hygienisation of separated solids. The estimates resulted in 40 m2/1,000 persons if solids are treated by co-composting, and in 70 m2/1,000 persons with solids treatment on sludge drying beds.

In addition to capital and annual O+M costs, it is obvious that the practice of FS dewatering in vertical-flow CWs without frequent removal of the dewatered FS results in significant savings in operating costs in contrast to unplanted sludge drying beds which require emptying at weeks' intervals.

CONCLUSIONS

The 3.5-year experimental results suggest that suitable operating conditions for the vertical-flow CW system treating septage of the type collected in the selected suburban districts of Bangkok be as follows:

i. SLR (solids loading rate) = 250 kg TS/m^2.yr or constant volume loading of 8 m^3/week
ii. Once-a-week application
iii. Percolate ponding period of 6 days

These operating conditions have resulted in optimum performance of the CWs with respect to FS dewatering and contaminant removal from the percolating liquid, healthy and reliable plant growth, and ease of operations in which removal of the dewatered FS was not required for a period of well over 3 years. The percolate ponding significantly enhanced nitrification/denitrification leading to a lowering of nitrogen loads in the percolate. Although more long-term data and full-scale operating experience are required, the results generated to date indicate that vertical-flow constructed wetlands constitute a promising, modest-cost technology for treating septage.

ACKNOWLEDGEMENT

The authors would like to thank Mr. Narong Surinkul, Mr. Surasak Limsuwan, Mr. Anawat Pinsakul, Mr. Roongrod Jittawattanarat, and Mr. Suprachoke Uakritdathikarn, for their valuable contributions in the operation and maintenance of the experimental CW units as well as the parameter analyses. The generous support from the Swiss Agency for Development and Cooperation (SDC) through a grant to EAWAG is gratefully acknowledged.

REFERENCES

APHA, AWWA, WPCF (1992). *Standard Methods for the Examination of Water and Wastewater*, 17th Edition, Washington, D. C..

Cooper, P.F., Job, G.D., Green, M.B., and Shutes, R.B.E. (1996). *Reed Beds and Constructed Wetlands for Wastewater Treatment*, WRc Swindon, Wiltshire.

Heinss, U. and Koottatep, T. (1998). *Use of Reed Beds for Faecal Sludge Dewatering*. EAWAG/AIT. Unpublished report.

Heinss, U., Larmie, S.A., Strauss, M. (1998). *Solids Separation and Pond Systems for the Treatment of Septage and Public Toilet Sludges in Tropical Climate - Lessons Learnt and Recommendations for Preliminary Design*. EAWAG/SANDEC Report No. 05/98.

Ingallinella, A.M., Sanguinetti, G., Koottatep, K., Montangero, A. and Strauss, M. (2001). The challenges of faecal sludge management in urban areas – strategies, regulations and treatment options. Paper to presented at the IWA Specialised Conference on Sludge Management: regulations, treatment, utilisation and disposal. Acapulco, Mexico, Oct. 25-27.

Johnstone, D.W.M., Horan, N.J. (1996). Institutional Developments, Standards and River Quality: An UK History and Some Lessons for Industrialising Countries. Water Science and Technology, **33**, No. 3, pp. 211-222.

Kadlec, R.H. and Knight, R.L. (1995). *Treatment Wetlands*, Lewis Publisher, New York.

Koottatep, T. and Polprasert, C., (1997). Role of plant uptake on nitrogen removal in constructed wetlands located in tropics, *Wat. Sci. & Tech.*, Vol. 36, No. 12, pp. 1-8.

Liénard, A. and Payrastre, F. (1996). Treatment of sludge from septic tanks in a reed-bed filters pilot plants, *Pre Prints of the 5th International Conference on Wetland Systems for Water Pollution Control*, Vienna, 8 p.

Limsuwan, S. (1997). Operational criteria for septage dewatering in constructed wetlands, *Master Thesis*, EV-97-45, Asian Institute of Technology, Bangkok.

Metcalf & Eddy (1991). *Wastewater Engineering – Treatment, Disposal, Reuse*. Irwin/McGraw-Hill. Third edition.

Montangero, A. and Strauss, M. (2000). Faecal Sludge Management – Strategic Aspects and Treatment Options, *Proc. of the International Workshop on Biosolids Management and UItilization at Nanjing and to the Forum on Biosolids Management and Uitilization*, Hongkong, September 2000.

Pinsakul, A. (1997). Nitrogen removal in constructed wetland beds treating septage, *Master Thesis*, EV-97-2, Asian Institute of Technology, Bangkok.

Polprasert, C. (1996). *Organic Waste Recycling*, 2nd edition, John Wiley & Sons, Chichester.

Schwartzbrod, J. (1998). *Quantification and Viability Determination for Helminth Eggs in Sludge (Modified USEPA Method).* Faculty of Pharmacy, Henri Poincaré University, PO Box 403, 54001 Nancy Cedex France.

Strauss, M., Heinss, U., Montangero, A. (2000). On-Site Sanitation: When the Pits are Full – Planning for Resource Protection in Faecal Sludge Management. In: *Proceedings, Int. Conference, Bad Elster, 20-24 Nov. 1998. Schriftenreihe des Vereins fuer Wasser-, Boden- und Lufthygiene,* **105***: Water, Sanitation & Health – Resolving Conflicts between Drinking – Water Demands and Pressures from Society's Wastes* (I.Chorus, U. Ringelband, G. Schlag, and O. Schmoll, eds.). IWA Publishing House and WHO Water Series. ISBN No. 3-932816-34-X.

United States Environmental Protection Agency (U.S. EPA) (1995). *Process Design Manual – Surface Disposal of Sewage Sludge and Domestic Septage*, Washington DC.

Xanthoulis, D. and Strauss, M. (1991). Reuse of Wastewater in Agriculture at Ouarzazate, Morocco (Project UNDP/FAO/WHO MOR 86/018). Unpublished mission/consultancy reports.