Integrated Eco-Engineering Design for Sustainable Management of Fecal Sludge and Domestic Wastewater

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Abstract : Constructed wetlands and other aquatic systems have been successfully used for waste and wastewater treatment in either temperate or tropical regions. To treat waste or wastewater in a sustainable manner, the integrated eco-engineering designs are explained in this paper with 2 case studies: (i) a combination of vertical-flow constructed wetland (CW) with plant irrigation systemfor fecal sludge management and (ii) integrated CW units with landscaping at full-scale application for domestic wastewater treatment. The pilot-scale study of fecal sludge management employed 3 vertical-flow CW units, each with a dimension of 5 x 5 x 0.65 m (width x length x media depth) and planted with cattails (Typha augustifolia). At the solid loading rate of 250 kg total solids (TS)/m2.yr and a 6-day percolate impoundment, the CW system could achieve chemical oxygen demand (COD), TS and total Kjeldahl nitrogen (TKN) removal efficiencies in the range of 80 - 96%. The accumulated sludge layers of about 80 - 90 cm was found at the CW bed surface after operating the CW units for 7 years, but no clogging problem has been observed. The CW percolate was applied to 16 irrigation Sunflower plant (Helianthus annuus) plots, each with a dimension of 4.5 x 4.5 m (width x length). In the study, the CW percolate were fed to the treatment plots at the application rate of 7.5 mm/day but the percolate was mixed with tap water at different ratio of 20%, 80% and 100%. Based on a 1-year data of 3-crop plantation were experimented, the contents of Zn, Mn and Cu in soil of the experimental plots were found to increase with increasing in CW percolate ratios. The highest plant biomass yield and oil content of 1,000 kg/ha and 35%, respectively, were obtained from the plots fed with 20% or 50% of the CW percolate, whereas no accumulation of heavy metals in the plant tissues (i.e. leaves, stems and flowers) of the sunflower is found. In addition to the pilot-scale and field experiments, a case study of the integrated CW systems for wastewater treatment at Phi Phi Island (a Tsunami-hit area), Krabi province, Thailand is illustrated. The 5,200-m^2 CW systems on Phi Phi Island are not only for treatment of 400 m3/day wastewater from hotels, households or other domestic activities, but also incorporating public consultation in the design processes, resulting in introducing the aesthetic landscaping as well as reusing of the treated effluent for irrigating green areas on the Island.

Keywords : Constructed Wetlands, Eco-engineering, Fecal Sludge, Integrated Systems

Introduction

In most developing countries where on-site sanitation systems are required, the accumulating solids or faecal sludge has to be periodically removed which is a nutrient-rich source but can contain high concentrations of toxic metals and chemicals and infectious micro-organisms such as E. Coli and helminth eggs. These harmful constituents may prohibit the reuses and recycling of valuable nutrients in FS such as nitrogen (N) and phosphorus (P). Compared with other sludge stabilization/dewatering systems, the constructed wetlands (CW) are found to be aneffective and promising alternative due mainly to its various treatment mechanisms including solids accumulation and mineralization, biodegradation, chemical precipi-

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tation and adsorption, nitrification/denitrification and plant uptake (Liénard and Payrastre, 1996; Nielsen, S. 2004). Since 1997, the pilot-scale vertical-flow CW units at AIT have been experimented by feeding fecal sludge at various operating conditions without removal of the accumulated sludge on CW surface. The 7-year experimental results could reaffirm the high treatment efficiencies of the vertical-flow CW system. Instead of discharging the CW percolate into the receiving streams, it should be reused in the agricultures or aquacultures where its nutrient constituents can be reclaimed. This pilot study aims to determine the effects of CW percolate on the sunflower plant irrigation by determining the material fluxes in terms of total solids, water, and nitrogen as well as elaborates the impacts of CW percolate on the growth of Sunflower plants and soil quality at various application rates.

This paper also describes the full-scale CW system for treating of domestic wastewater in Phi Phi Island where the landscaping was introduced into the design. This was based on the concept that people will actively participate and undertake the operating, maintenance and monitoring the systems if the wastewater treatment plant becomes their park-like environment. The design with more aesthetic values should enable the sustainability of CW system locating on the Island about 40 km from mainland.

Materials and Methods

Experimental Setup

CW units - Three pilot-scale CW units, each with a surface area of 5x5 m and a 65-cm substrata layer, were established in AIT campus and operated in a vertical-flow mode. The substrata in CW units comprise a 10-cm layer of fine sand, a 15-cm layer of small gravel, and 40-cm layer of large gravel from topto bottom, while a free board of 1 m was allowed for accumulation of dewatered sludge. Each CW unit was planted with cattails (*Typha augustifolia*) having hollow concrete blocks as a drainage system and the perforated PVC pipes with a diameter of 20-cm. Mounted on the drainage system are ventilation pipes of the same diameter and extending approximately 1 m over the top edge of the units (Fig. 1). FS from Bangkok city have been fed into CW units at the solid loading rate of 1.5–9.6 kgTS/m^2.week (average 4.8 kgTS/m^2.week) with the percolate impounding periods of 2–12 days.

Sunflower plant plots – Adjacent to the CW units, the experimental plots were prepared according tothe randomized complete block design

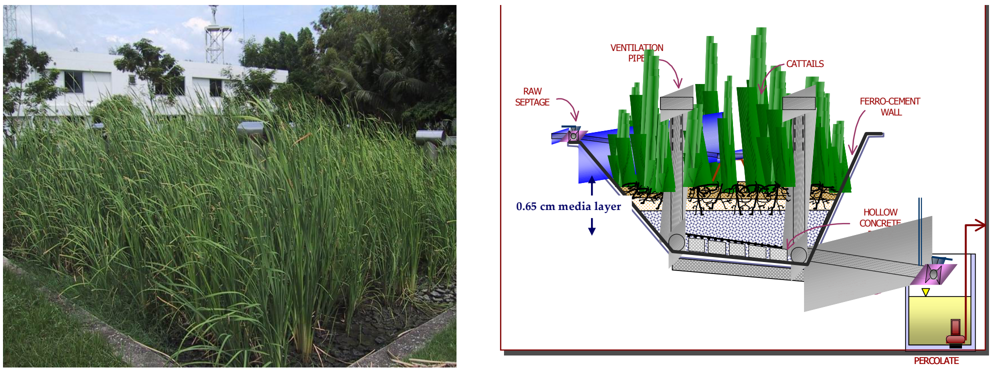

Fig. 1. Photo and schematic diagram of pilot-scale CW units

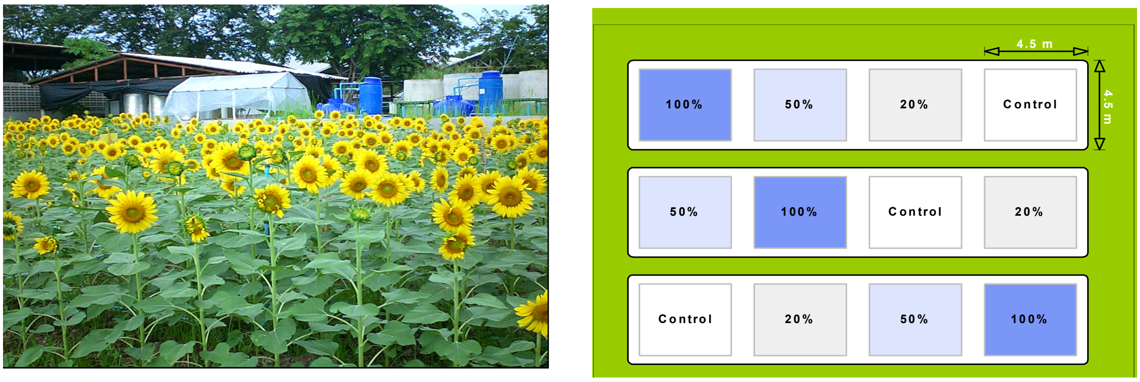

Fig. 2. Photo and layout of sunflower experimental plots

with 12 treatment plots (Fig. 2); each with dimension of 4.5 x 4.5 m2. In a treatment plot, the CW percolate were irrigated at a rate of 7.5 cm/day at the different CW ratio: 20%, 50% and 100%, while the control plots were irrigated with only tap water. The experiments were undertaken during June 2004 to March 2005, resulting in 3 crops of sunflower plantation. Sunflower plants (Helianthus annuus), short-season crop and requiring low management, were planted in the experimental plots at the density of 2.4 plants/m^2. Leaves, stem, flower disc, roots and seeds of sunflower plants were collected and analyses for metal contents at flowering and harvesting stages as shown in Table 2.

Percolate and soil analyses - Two samples of percolate per month were collected from the CW units before irrigating onto the experimental plots. Physical and chemical parameters of the CW percolate including chemical oxygen demand (COD), total solid (TS), total Kjeldahl nitrogen (TKN), ammonium (NH_4), nitrate (NO_3), total phosphorus (TP), phosphate (PO_4), total potassium (TK), Zn, Mn and Cu were analyzed according to Standard Methods of Water and Wastewater Analysis (1998). The structure of soil with heavy clay in texture is weak-coarse to blocky and slow permeability. Composite soil sample were collected from 0-15 and 15-30 cm depths at three stages: prior to planting, during flowering and after harvesting stages. Soil sample were immediately air dried for 2-3 days. Parameters and analytical methods for soil characteristics were similar to those for plant samples but different extraction methods.

Phi Phi Island after Tsunami-hit − After the catastrophic incidence in December 2004, several infrastructures and dwellings on Phi Phi Island, a world-famous tourist attraction of Krabi province in Southern Thailand, were drastically damaged (Fig. 3) as well as hundreds of dead persons. Unavoidably, the wastewater treatment systems were heavily destroyed resulting in the discharge of untreated wastewater into the sea. Even before the year 2004, the 4-m depth waste stabilization ponds at a design capacity of 400 m^3/day were not properly functioned likely because of the poor operation and maintenance. Local people and tourists perceived these ponds as stinky and smelly units locating in the center of Island. With the generous supports of Danish government, the wastewater treatment systems were rehabilitated using the integrated constructed wetlands with the public consultation.

Fig. 3. Damages of wastewater treatment systems on Phi Phi Island

Results and Discussion

Pilot-scale CW units treating FS and sunflower plant irrigation

Treatment Performance

Based on the experimental results obtained during 1997 - 2003, it found that CW units operating at different solid loading rate (SLR) and impounding periods could obtain the relatively high treatment efficiencies (Table 3) such as TS removal of 73%; COD removal of 97%; TKN removal of 94%, and NH_3 removal of 92% (Koottatep *et al.*, 2004). It could be noticed that the solid loading rates of 4.8 $kgTS/m^2$.week of this experiments were doubled of those investigated by Nielsen, 2004, but able to achieve the same magnitude of removal efficiencies without adverse effects on the plant growth. Due to the nitrification reaction in the CW units, NO_3 concentrations in the CW percolate were found to be higher that those in the raw FS. However, the increase of NO_3 concentrations in CW percolate depends on the impounding period, likely resulting from the denitrification reaction in CW units. For instance, the NO_3 concentrations in the percolate of CW unit with no impounding were increased from 0 to 106 mg/L, whereas the CW unit with 12-day impounding can obtain the NO_3 concentration of 13 mg/L.

Varying the FS loading frequency between once- and twice-a-week showed insignificant effects on treatment performance but twice-weekly loading helped support the growth of cattails during operations without percolate im-

Table 1. Treatment performance of pilot-scale CW units treating FS

Unit No.	Impounding periods, day	Parameters, mg/L					
		SS	TS	COD	TKN	NH_3	NO_3
Raw FS		11,820	13,710	14,485	993	412	9
Percolate		(% removal)					
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

pounding. To minimize the workload in FS 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 FS loading.

Mass Balances in CW units

Mass balance analysis of water, solid and nitrogen across the CW beds treating FS using 1-year experimental revealed that half of the water in FS was lost due to the evapo-transpiration, and 45% was drained out as percolate, while the rest, 5%, was retained in the accumulated sludge. The TS mass retained on the CW bed accounted for 50%, while TS in the percolate was 11%. It can be inferred that the rest (39%) of the TS mass constituted the unaccounted for balance, which had undergone biochemical reactions such as mineralization and solids accumulation in the wetland substrata. The N mass in the accumulated FS and CW percolate accounted for only 13% and 5%, respectively, of the total N loaded in the FS. Losses of N from CW units of about 82% could be due to ammonia volatilization, denitrification, microbial and plant uptake, and N accumulation in the CW substrata.

Characteristics of accumulated sludge

The solids accumulation rate amounted to 12 cm per year, resulting in an 80-cm sludge layer after seven years of continuousFS loading. In spite of this extended loading without removal of accumulated sludge, 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. According to the sludge characteristics as shown in Table 4, TVS contents have reduced substantially from 64% in Sep 2000 to 41% in Feb 2003, likely due to gradual mineralization of organic contents in the sludge. On the contrary, the TS concentration in biosolid was increased from 29% to 47%. No significant change in the sludge characteristics in termsof available nutrients, viz. available-N, available-P and available-K concentrations has been observed. It was also found that the available N, P, and K accounted for about 5 − 8% of the total N, P and K contained inthe accumulated solids (Table 2).

Table 2. Characteristics of accumulated sludge in CW units

Period	Avail-N* (mg/kg)	Avail-P (mg/kg)	Avail-K (mg/kg)	TS (%)	TVS (%)
September 2000	1,000	3,400	135	29	64
August 2001	-	-	-	36	55
May 2002	-	-	-	57	47
February 2003	1,060	3,922	152	47	41

Note: Loading of raw FS in CW unit 2 was stopped in May 2000

Sunflower seed yields and oil contents

The first crop of sunflower plantation could achieve the average seeds yield ranging from 794 to1, 261 kg/ha. Fig. 4 shows the average sunflower seed yield of three cropsof sunflower plantation. It could be observed that seed yields increased with increasing percolate applications from 20–50% while at the 100% percolate seed yield was decreased. The highest seed yield occurred at the plot applied with 50% percolate at the yield of 1,261 kg/ha, while the lowest occurred at control plot with the yield of 794 kg/ha. Oil contents in sunflower seeds were measured by analyzing seed after harvesting stage. Fig. 5 shows the average oil percentages from three crops of sunflower plantation. The highest oil content was found at the 50% percolate plot, slightly higher than the 20% percolate plot. For the control and 100% percolate plots were 34%and 31% respectively, slightly lower than the typical oil content of 40%.

Soil characteristics

It could be observed from sunflower plantation, flowering and harvesting stages that there is no significant change in the soil pH of each treatment. Soil N contents of the 100% percolate plot showed some increase from 1.1 - 1.5 g/kg at the top soil 0-15 cm and 0.7 - 1.3 at top soil of 15 - 30 cm. On the contrary, likely due to the leaching effects of percolate irrigation, the TP contents in soil were decreased inall treatments. However, the highest TP concentration was found at the 100% percolate plot while the lowest was found at the control plot. The maximum available P concentration was found at the 100% percolate plots at the concentration of 25 and 19 mg/kg and the lowest was found at the 20% percolate plot at the concentration of 15 and 14 mg/kg in top soil of 0-15 and 15-30 cm, respectively. Available K contents in soil were decreased at flowering and harvesting stage. The decreased in available K contents due to plant uptake (exchangeable forms) and downward leaching beyond the sampling depth.

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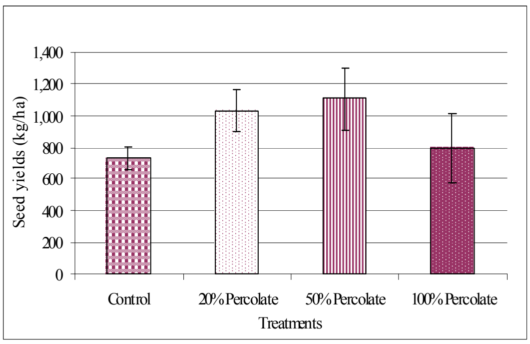

Fig. 4. Average sunflower seed yields

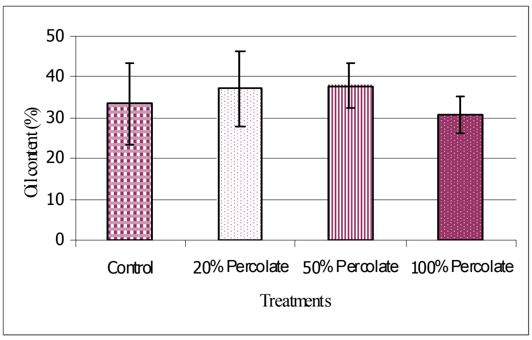

Fig. 5. Oil content of sunflower seeds

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Rehabilitation of wastewater treatment system on Phi Phi Island

The challenges in rehabilitation of the wastewater treatment systems on Phi Phi Island are due to the public resistance to waste stabilization ponds whereas the conventional systems such as activated sludge processes are not preferable because of the high costs as well as the sophistication in operation and maintenance. Based on the public consultative meetings, it recommended that the CW system should be a promising treatment alternative for this Island with great consideration of the sustainability of the systems. Furthermore, because of the fresh water scarcity, the meeting suggested that the waste treatment system produce the effluent at the acceptable quality for plant irrigation.

Conceptual design of the CW systems includes the integration of different flow patterns

Table 3. Soil pH and macronutrients from top soil of 0-15 and 15-30 cm (average from 3 crops of sunflower plantation)

	Treatment	0-15 cm. (soil depth)					15-30 cm. (soil depth)				
		pH	Total N (g/kg)	Total P (mg/kg)	Avail. P (mg/kg)	Avail.K (mg/kg)	pH	Total N (g/kg)	Total P (mg/kg)	Avail. P (mg/kg)	Avail.K (mg/kg)
Before treatment	Control	6.4	1.00	182	25	192	5.9	1.00	146	9	177
	20% Percolate	6.6	1.40	188	21	172	6.0	1.20	154	8	176
	50% Percolate	6.6	0.90	186	16	143	5.8	0.70	147	13	132
	100% Percolate	6.7	1.10	188	20	159	6.2	0.70	151	9	129
Flowering stage	Control	6.2	0.90	34	25	175	6.1	0.80	27	20	114
	20% Percolate	6.3	0.08	31	19	155	6.3	0.90	24	12	109
	50% Percolate	6.6	1.00	31	12	107	6.6	0.70	26	6	68
	100% Percolate	6.6	1.40	30	22	184	6.7	1.20	24	9	63
Harvesting stage	Control	5.9	0.80	28	24	120	6.1	0.90	24	15	108
	20% Percolate	6.4	0.90	36	15	117	6.4	0.90	33	14	101
	50% Percolate	6.1	1.00	36	16	89	6.1	1.00	29	21	73
	100% Percolate	6.5	1.50	39	25	102	6.6	1.30	34	19	68

Source: Hadsoi (2005)

in series: vertical-flow; horizontal subsurface flow and free water surface in order to ensure the effluent quality. This integrated CW system was designed at the capacity of 400 m^3/day for treating effluent from septic tanks and grey-water from households, restaurants, hotels and other dwellings. To prevent odor problem at the manholes and to avoid rainwater dilution at the combined sewer system, the wastewater was collected by a separated sewer system and pumping to the CW units.

Schematic drawings of "the flower and the butterfly" CW design is shown in Fig 5 by which the wastewater is fed to the "flower"vertical-flow and horizontal subsurface flow units before feeding to the "butterfly" free water surface units (CD-WMA, 2005). Total surface area of CW units is 8,200 m^2, each having 60 cm gravel media. The treated effluent is collected at a 100-m^3 underground tank where the local people can use for irrigation their gardens otherwise it will be discharged to the sea. The CW units are planted with Canna, Heliconia, and Scirpus in vertical-flow; horizontal subsurface flow and free water surface units, respectively, most of which are colorful flowers. In addition, some other plants and flowers are planted with the landscaping design as a community park (Fig. 6).

Fig. 5. Schematic diagram of integrated CW system of Phi Phi Island

Fig. 6. Bird-eye-view of "The Flower and The Butterfly" CW system

According to the design criteria for CW units, the integrated CW systems can treat the wastewater with BOD and TKN concentrations of 100 and 20 mg/L, respectively. It is expected that BOD and TKN concentrations of the treated effluent should below 10 and 5 mg/L, respectively. However, long-term monitoring data of the CW systems are required to prove their treatment efficiencies.

Conclusions

Based on the abovementioned case studies on the pilot-scale study at AIT and the full-scale application on Phi Phi Island, it could demonstrate that the integrated eco-engineering design could offer a sustainable treatment alternative for fecal sludge and domestic wastewater. The experimental results of pilot-scale study revealed that at the solid loading rate of 4.8 kg total solids (TS)/m^2.week and a 6-day percolate impoundment, the CW system treating fecal sludge could achieve COD, TS and TKN removal efficiencies in the range of 80 - 96%. The residual nutrients in the CW percolate could also be reclaimed through sunflower plant irrigation, which are evidently safe for oil consumption or soil contamination. The optimum ratio of percolate was found to be in the range of 20 −50% at the application rate of 7.5 mm/day, which could result in the highest seed yield and oil content and having metal accumulation in soil and plant tissues below the acceptable limits.

Integrated eco-engineering design can also be applied for wastewater management in a remote Island which should offer the minimal operation and maintenance but capableof treating the wastewater up to the effluent standards for reuse and recycling. Integration of the CW systems is not only refer to the combination of various CW types or plant species, but also incorporating public consultation into the design process that should enable the sustainable operation and maintenance of CW system.

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