Integrated faecal sludge treatment and recycling through constructed wetlands and sunflower plant irrigation

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Abstract Faecal sludge (FS) from the on-site sanitation systems is a nutrient-rich source but can contain high concentrations of toxic metals and chemicals and infectious micro-organisms. The study employed 3 vertical-flow CW units, each with a dimension of 5 × 5 × 0.65 m (width × length × media depth) and planted with cattails (*Typha augustifolia*). At the solid loading rate of 250 kg total solids (TS)/m^2.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%. A solid layer of about 80 cm was found accumulated on 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 × 4.5 m (width × length). In the study, tap water was mixed with 20%, 80% and 100% of the CW percolate at the application rate of 7.5 mm/day. Based on a 1-year data in which 3 crops of plantation were experimented, the contents of Zn, Mn and Cu in soil of the experimental plots were found to increase with increase in CW percolate ratios. In a plot with 100% of CW percolate irrigation, the maximum Zn, Mn and Cu concentrations of 5.0, 12.3 and 2.5 mg/kg, respectively, were detected in the percolate-fed soil, whereas no accumulation of heavy metals in the plant tissues (i.e. leaves, stems and flowers) of the sunflower were detected. The highest plant biomass yield and oil content of 1000 kg/ha and 35%, respectively, were obtained from the plots fed with 20% or 50% of the CW percolate.

Keywords Faecal sludge; nutrient recovery; percolate reuse and recycle; sunflower plants; vertical-flow constructed wetlands

Introduction

The accumulating solids in on-site sanitation systems or faecal sludge (FS), which have to be periodically removed, are 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 reuse and recycling of valuable nutrients in FS such as nitrogen (N) and phosphorus (P). In addition, the high organic and solid contents in FS need to be properly stabilized prior to agricultural or aquacultural reuse. Among several low-cost sludge stabilization/dewatering systems, the constructed wetlands (CW) are an effective and promising alternative due mainly to its various treatment mechanisms including solids accumulation and mineralization, biodegradation, chemical precipitation and adsorption, nitrification/denitrification and plant uptake (Liénard and Payrastre, 1996; Koottatep *et al.*, 2005). For treatment of sludge with high solid concentration, a vertical-flow CW unit is desirable because it directs the flow downwards through the filtering media to the drainage system. Since 1997, the pilot-scale vertical-flow CW units at AIT have been experimented by feeding FS at various operating conditions without removal of the accumulated sludge on the CW surface. The 7-year experimental results could reaffirm the high treatment efficiencies of

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the vertical-flow CW system. However, the pollutant concentrations in the CW percolate remained somewhat higher than the effluent discharge standards. Instead of discharging into the receiving streams, the CW percolate should be reused in agriculture or aquaculture where its nutrient constituents can be reclaimed. In order to avoid public health concerns, this study aims to determine the effects of CW percolate on sunflower plant irrigation. This paper describes the material fluxes in the CW units treating FS 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.

Methods

Experimental setup

CW units. Three pilot-scale CW units, each with a surface area of 5 × 5 m and a 65 cm substrata layer, were established at the Environmental Research Station of AIT 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 top to bottom, while a free board of 1 m was allowed for accumulation of dewatered sludge. Each CW unit was planted with narrow-leaved cattails at an initial density of 10–15 shoots/m^2. The drainage system of the CW unit includes hollow concrete blocks, each with dimensions of 20 × 40 × 16 cm (width × length × hollow space), and 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 (Figure 1). Operating conditions of the CW units are shown in Table 1.

Sunflower plant plots. Adjacent to the CW units at the AIT Environmental Research Station, the experimental plots were prepared according to the randomized complete block design with 12 treatment plots (Figure 2); each with dimension of 4.5 × 4.5 m^2. In a treatment plot, the CW percolate was irrigated at a rate of 7.5 cm/day at different CW ratios: 20%, 50% and 100%, while the control plots were irrigated with only tap water.

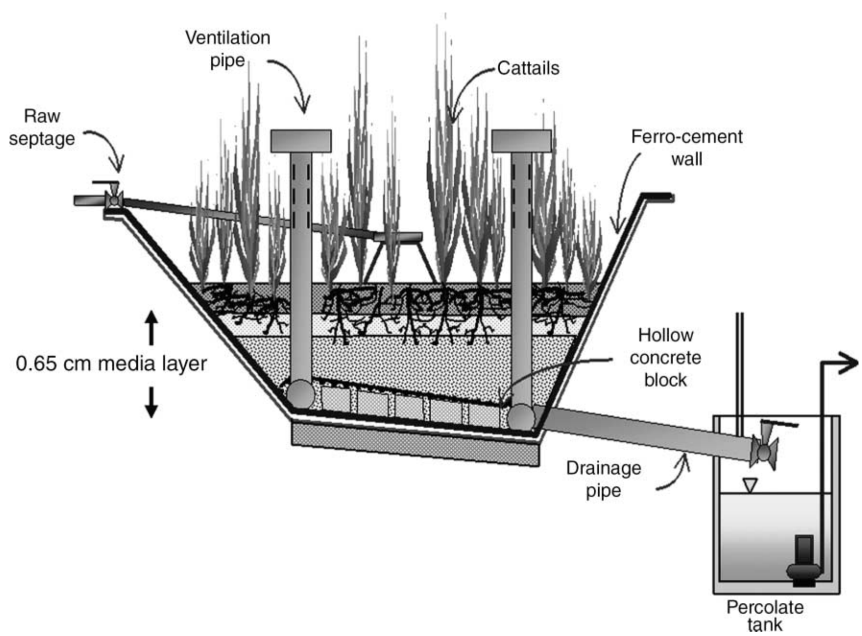

Figure 1 Schematic diagram of CW units

Table 1 Operating conditions of CW units treating FS during 1997–2003

Run	Solid loading rate (SLR), kgTS/m^2.week			Percolate impounding*	Frequency of FS application	Period of operation
	CW-1	CW-2	CW-3			
1	4.8	2.4	1.5	No	Once + twice-a-week	Apr. 97–Dec. 97
2	9.6	4.8	3.0	No	Once + twice-a-week	Dec. 97–Jan. 98
3	4.8[a]	4.8[b]	4.8[c]	Yes	Once-a-week	Feb. 98–May. 98
4	4.8[a]	4.8[b]	4.8[c]	Yes	Once-a-week	Jul. 98–Feb. 99
5	4.8[a]	4.5[b]	4.8[c]	Yes	Once-a-week	Mar. 99–Aug. 99
6	4.5[d]	4.8[a]	–	Yes	Once-a-week	Sep. 99–May. 00
7	4.8[a]	–	–	Yes	Once-a-week	Jun. 00–Dec. 01
8	4.8[a]	–	–	Yes	Once-a-week	Jan.02–May. 03

*Percolate was retained 10–15 cm below dewatered FS layers in CW units
+Loading 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

The experiments were undertaken during June 2004 to March 2005, resulting in 3 crops of sunflower plantation.

Sunflower plants (*Helianthus annuus*), a short-season crop requiring low management, were planted in the experimental plots at a 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 are shown in Table 2. Seeds were removed from the sunflower disc by hand; root, stem and leaf were well washed with deionized water before drying to remove any surface contamination, The collected samples were dried at 80 °C for 48 hours for the determination of moisture contents and then the dry plants were ground to pass through a 2 mm sieve prior to analysis.

Percolate analysis. 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),

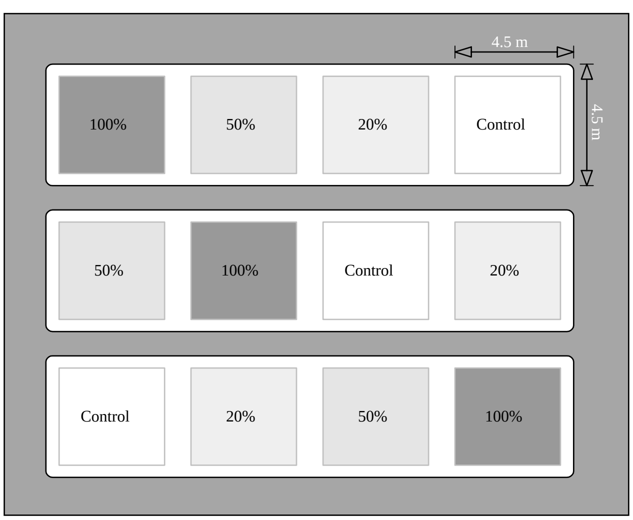

Figure 2 Layout of sunflower experimental plots

Table 2 Parameters and analytical methods of plant samples (some information sourced from MOAC – Ministry of Agriculture and Cooperatives, Bangkok, Thailand)

Parameter	Analytical method
Biological Parameter	
- Height	Measure from the soil surface to the end of highest leave
- Flowering date	Record 50% flowering of the plant in each plot
- Physical maturity date	Record when 70–80% of grains are black. (MOAC, 2001)
- Biomass	Harvest all aboveground biomass, close to the ground. Oven dry at 80°C to constant weight then weigh
- Grain	Measure from biomass harvest area by weigh total grain weigh from each plot, converse to the weight at 12% of moisture content
Chemical Parameter	
- Total Nitrogen	The same sample of biomass will be sampling and analyze for nitrogen uptake by Total Kjeldahl Nitrogen (MOAC, 1994)
- Zinc (Zn)	Atomic absorption spectrophotometer
- Manganese (Mn)	Atomic absorption spectrophotometer
- Copper (Cu)	Atomic absorption spectrophotometer
- Oil content in sunflower seeds	Extraction (MOAC, 2001)

phosphate (PO4), total potassium (TK), Zn, Mn and Cu were analyzed according to *Standard Methods for the Examination of Water and Wastewater* (1998).

Soil analysis. The soil in the experimental plots can be classified as Sulfic Tropaquepts with heavy clay in texture. The structure of the soil is weak-coarse to blocky with slow permeability. Composite soil samples were collected from 0–15 and 15–30 cm depths at three stages: prior to planting, during flowering and after harvesting stages. Soil samples were immediately air dried for 2–3 days. After drying, soil samples were ground to pass a 2 mm sieve prior to analysis. Parameters and analytical methods for soil characteristics were similar to those for the plant samples but with different extraction methods.

Results and discussion

Treatment performance

Based on the experimental results obtained during 1997–2003, it was 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%. It could be noticed that the solid loading rates of 4.8 kgTS/m^2.week of these experiments were twice those investigated by Nielsen (2005), 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 the

Table 3 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)	3886 (73)	349 (97)	56 (94)	30 (92)	13
1	6	111 (99)	3112 (78)	289 (98)	90 (91)	62 (85)	36
2	2	228 (98)	2557 (82)	459 (97)	139 (86)	99 (76)	50
3	0	391 (97)	3035 (78)	803 (95)	198 (80)	140 (66)	106

CW units. For instance, the NO_3 concentrations in the percolate of the 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 impounding. 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 balances of water, solid and nitrogen across the CW beds treating FS using 1-year experimental results are depicted in Figure 3. It can be seen 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 continuous FS 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 shown in Table 4, TVS contents have reduced substantially from 64% in Sep. 2000 to 41% in Feb. 2003, likely due to gradual mineralization

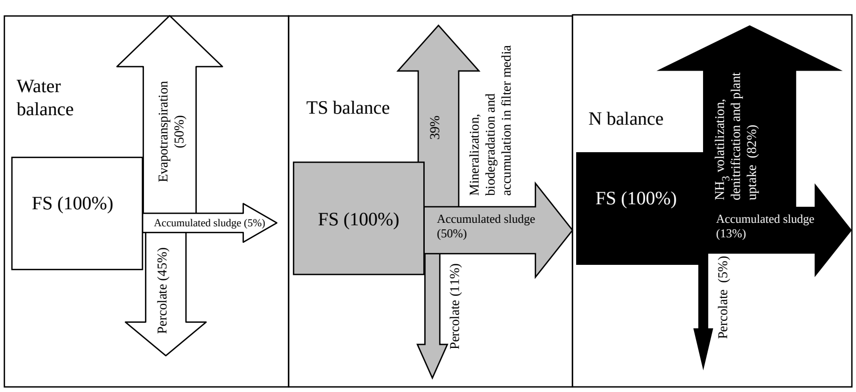

Figure 3 Water, TS and N balance in CW units treating FS

Table 4 Characteristics of accumulated sludge in CW units

Period	Avail-N* (mg/kg)	Avail-P (mg/kg)	Avail-K (mg/kg)	TS (%)	TVS (%)
September 2000	1000	3400	135	29	64
August 2001	–	–	–	36	55
May 2002	–	–	–	57	47
February 2003	1060	3922	152	47	41

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

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 terms of 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 in the accumulated solids (Table 5), which together with pathogens and heavy metals are important criteria for determining the suitability of sludge for agricultural applications. Sludge samples were collected from the upper (15 cm from surface) and deeper (45 cm from surface) layers of the CW units.

Effects of CW Percolate Irrigation

Sunflower seed yields and oil contents. The first crop of sunflower plantation could achieve average seeds yield ranging from 794 to1, 261 kg/ha. Figure 4 shows the average sunflower seed yield of three crops of sunflower plantation. It could be observed that seed yields increased with increasing percolate applications from 20 to 50% while at 100% percolate, seed yield was decreased. The highest seed yield occurred at the plot applied with 50% percolate at the yield of 1261 kg/ha, while the lowest occurred at a control plot with a yield of 794 kg/ha.

Oil contents in sunflower seeds were measured by analyzing seed after the harvesting stage. Figure 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. The control and 100% percolate plots were 34 and 31% respectively, slightly lower than the typical oil content of 40%.

Soil characteristics. Table 5 shows the soil characteristics in sunflower plots during sunflower plantation, flowering and harvesting stages. It could be observed 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 to 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 the soil were decreased in all 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 concentrations of 25 and 19 mg/kg and the lowest was found at the 20% percolate plot at concentrations 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 the flowering and harvesting stage. The decrease in available K contents was due to plant uptake (exchangeable forms) and downward leaching beyond the sampling depth.

Heavy metals accumulation in soil. Table 6 shows available heavy metal content in soil before treatment, flowering and harvesting stages. It is apparent that the control and 50% percolate plots had average available Zn contents decreased at the flowering stage and

Table 5 Soil pH and macronutrients from top soil of 0–15 and 15–30 cm (average from 3 crops of sunflower plantation)

	Treatment	pH	0–15 cm (soil depth)				pH	15–30 cm (soil depth)			
			Total N (g/kg)	Total P (mg/kg)	Avail. P (mg/kg)	Avail.K (mg/kg)		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)

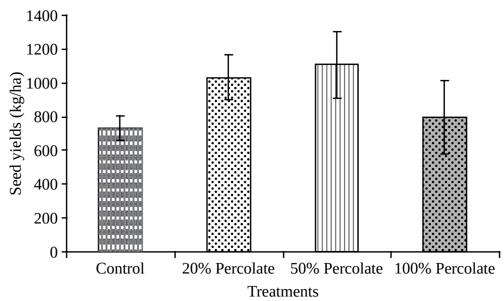

Figure 4 Average sunflower seed yields

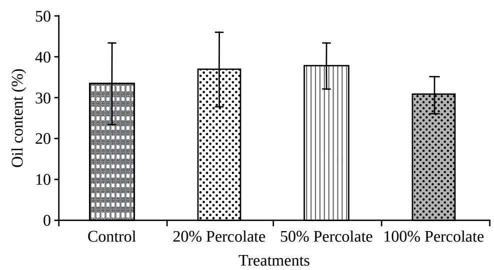

Figure 5 Oil content of sunflower seeds

increased at the harvesting stage, while soil Zn contents in other treatment plots were decreased with time at both soil depths. The available Mn contents in soil was increased from initial soil at both flowering and harvesting stages, while available Cu concentration was decreased at all treatment plots. The decrease in total Zn, Mn and Cu contents in soil was perhaps due to plant uptake (exchangeable form) and downward leaching beyond the sampling depth (Khanal, 1997).

N and metal contents in sunflower plants. Table 7 shows total N contents in leaf, stem, flower disc, root and seed of sunflower plants at the flowering and the harvesting stages. It is apparent that total N in the sunflower plant was increased from 0.90–1.21% at the harvesting stage to be 2.28–3.35% at the flowering stage. The maximum

Table 6 Available heavy metals accumulation in soil

	Treatment	0–15 cm (soil depth)			15–30 cm (soil depth)		
		Zn (mg/kg)	Mn (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	Cu (mg/kg)
Before treatment	Control	4.9	8.9	5.8	4.5	9.4	5.4
	20% percolate	2.9	7.1	5.4	3.7	7.5	5.0
	50% percolate	3.7	7.0	5.5	3.3	8.6	5.1
	100% percolate	3.7	7.6	5.6	3.8	8.1	5.1
Flowering stage	Control	2.7	9.7	3.2	3.1	8.5	3.1
	20% percolate	3.2	10.3	2.9	3.1	8.9	3.0
	50% percolate	2.7	8.6	2.8	3.2	11.4	2.8
	100% percolate	6.4	10.7	2.8	4.6	7.7	2.8
Harvesting stage	Control	4.6	13.9	2.9	4.3	16.4	3.5
	20% percolate	3.0	11.8	2.4	3.5	11.6	4.2
	50% percolate	5.1	12.1	2.6	3.4	11.1	2.8
	100% percolate	5.0	12.3	2.5	5.3	13.3	3.6

Source: Hadsoi (2005)

Table 7 N, contents in various portions of sunflower plants

	Treatment	Plant material (% N in dry matter)					Total
		Leaf	Stem	Flower disc	Root	Seed	
Flowering stage	Control	0.45	0.09	0.24	0.12	–	0.90
	20% percolate	0.50	0.10	0.26	0.13	–	0.99
	50% percolate	0.53	0.10	0.28	0.12	–	1.03
	100% percolate	0.56	0.14	0.32	0.19	–	1.21
Harvesting stage	Control	0.64	0.11	0.33	0.27	0.93	2.28
	20% percolate	0.70	0.13	0.34	0.28	0.94	2.39
	50% percolate	0.77	0.15	0.38	0.30	1.05	2.65
	100% percolate	0.81	0.25	0.63	0.43	1.28	3.40

Source: Hadsoi (2005)

Table 8 Zn, and Mn contents in various portions of sunflower plants

	Treatment	Zn (mg/kg dry matter)					Mn (mg/kg dry matter)				
		Leaf	Stem	Flower disc	Root	Seed	Leaf	Stem	Flower disc	Root	Seed
Flowering stage	Control	87	96	68	100	–	57	51	25	20	–
	20% percolate	106	64	82	54	–	74	18	25	19	–
	50% percolate	129	53	59	52	–	52	18	22	20	–
	100% percolate	145	66	46	66	–	149	16	27	21	–
Harvesting stage	Control	91	50	45	113	45	58	22	20	19	19
	20% percolate	87	57	46	103	55	72	21	27	19	18
	50% percolate	78	62	38	118	64	72	21	24	21	22
	100% percolate	142	63	57	132	77	94	25	45	23	21

Source: Hadsoi (2005)

N contents were found from the plots with 100% percolate irrigation, either in flowering or harvesting stages. In addition, N contents in the sunflower plants from the plots with percolate irrigation are significantly higher than those from the plots with tap water.

As shown in Table 8, total Zn content in plants in the cultivating stage was higher than the harvesting period. The maximum Zn content in sunflower plants was found at the 100% percolate plot, while the lowest was found at the control plot. The maximum Mn content in the sunflower plant was found at the 100% percolate plot, both flowering and harvesting, while the lowest was found at the 50% percolate plot. The experimental results obtained from three crops plantation suggested that no significant effects of the Mn accumulation in sunflower seeds be observed after percolate irrigation in the sunflower plots.

Conclusions

Based on the experimental results obtained to date, it could be concluded 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 chemical oxygen demand (COD), TS and total Kjeldahl nitrogen (TKN) removal efficiencies in the range of 80–96%. The residual nutrients in the CW percolate could also be recycled through sunflower plant irrigation, which are evidently safe for oil consumption or soil contamination. The experimental results suggested the optimum ratio of percolate is in the range 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. However, long-term field experiments on the application of CW percolate to sunflower plants are recommended to assess the impacts of salinity accumulation in the soil and the socio-economic implications of this practice.

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