EnvironmentAsia
The international journal published by the Thai Society of Higher Education Institutes on Environment

Available online at www.tshe.org/EA
EnvironmentAsia 7(2) (2014) 45-53

Improvement of Groundwater Quality Using Constructed Wetland for Agricultural Irrigation

Pantip Klomjek [a] and Kasem Chunkao [b]

[a] *Faculty of Agriculture, Natural Resources and Environment, Naresuan University, Phitsanulok, 65000, Thailand*
[b] *The Leam Phak Bia Environmental Study Research and Development Project underRoyal Initiatives, Petchaburi, 76100, Thailand*

Abstract

This research was designed to evaluate the performance of Constructed Wetlands (CW) for groundwater quality improvement. In the first phase of this study, performance of CW planted with cattails for Manganese (Mn) and Iron (Fe) reduction was evaluated at 12, 24 and 48 hours of Hydraulic Retention Time (HRT). Average efficiencies of all tested CW systems were higher than 90 and 75% for Mn and Fe concentration reduction. Subsequently, the efficiency of CW operated at 12 hours of HRT was investigated at different plant harvest intervals. In the second phase of study, Mn and Fe removal efficiencies were 75-100 and 48-99%, respectively. Both Mn and Fe removal efficiencies for the CW system were not different between 4, 6 and 8 weeks of harvest intervals. However, the efficiency obviously increased after the first plant harvest. Average Mn and Fe removal rates of the CWs operated at the tested harvest intervals were 0.068 to 0.092 and 0.383 to 0.432 g/m^2/d, respectively. Fe removal rate was not significantly different under the various test conditions. However the highest Mn removal rate was obtained in CWs operated with a harvest interval of 4 weeks. Mn accumulation rates in cattail shoots and roots were 0.04-8.25 and 0.83-23.14 mg/m^2/d, respectively. Fe accumulation rates in those were 0.04-164.27 and 249.62-1,701.54 mg/m^2/d, respectively. Obviously, cattail underground tissues accumulated both Mn and Fe at higher concentrations than those of the aboveground tissue. These results show that CW can improve the quality of groundwater before agricultural irrigation.

Keywords: groundwater; constructed wetland; heavy metal; hydraulic retention time; plant harvest

1. Introduction

Groundwater is an important resource for agricultural, municipal and industrial uses, especially in non-irrigation areas and during the dry season. Normally, groundwater is appropriate for use as water supply because it flows through natural filter materials such as soil pores and fractures of rocks beneath ground surface. However, in some areas groundwater contains high dissolved metals such as Fe and Mn that may affect the applications. High Fe concentrations in groundwater for municipal use cause unsightly deposits on equipment and buildings, as well as staining laundry and sanitary ware. Agriculturally, Fe in water can contribute to soil acidification and a reduction in the availability of essential nutrients like phosphorus and molybdenum. Because Fe and Mn take a role as phosphorus reservoir, excessive amounts of these metals can induce symptoms of phosphorus deficiency in plants. As reported by Becker and Asch (2005), high ferrous ion (Fe^{2+}) concentration in anaerobic and acidic soils could lead to Fe toxicity as a result of excessive Fe uptake by plants. Subsequently, Sahrawat (2005) revealed that Fe toxicity caused a reduction in rice yields from 12 to 100%, depending on the Fe tolerance of the genotype, intensity of Fe toxicity stress, and soil fertility status. Mn is also toxic to numerous crops including rice, but usually only in acid soils. It is known that excess Mn is frequently associated with decrease of grain yield (Nelson, 1983). Furthermore, oxygen released by rice roots under anaerobic conditions will stimulate plague formation or Fe and Mn deposition on rice root surface which limits uptake of essential nutrients.

Paddy rice is one of the most important crops in Phitsanulok province, located in the lower northern region of Thailand. In this region, large volumes of groundwater with high Fe and Mn concentrations are pumped for rice cultivation every year. As a result, an accumulation of these metals in paddy soils occurs through use of groundwater (Yimprae, 2004). Consequently, farmers in this area are confronted with several problems arising from groundwater with high Fe and Mn concentrations. Therefore, groundwater quality improvement is desirable, and an appropriate treatment system for Fe and Mn removal is required. In this research, CWs were evaluated as a treatment system, because such techniques are widely used for heavy metal reduction in many kinds of wastewater (Khan *et al*., 2009; Kröpfelová *et al*., 2009; Lesley *et al*., 2008). Moreover, CW is a cost effective and operationally simple system that is environmental friendly (Kadlec and Knight, 1996; Khan *et al*., 2009; Yeh *et al*., 2009). Therefore, the performance of CW for groundwater quality improvement was investigated. In addition, we investigated operation practices to maintain a high efficiency of Fe and Mn removal.

2. Materials and Methods

2.1. Experimental setup and operation

Experimental units with the dimensions of 0.50 x 2.0 x 0.85 m were set up as CW systems at Naresuan University, Phitsanulok, Thailand. Each plot was filled with soil to a depth of 70 cm to support emergent macrophyte (Fig. 1). Because a cattail can grow in wide range of conditions, it is often used in constructed wetlands (U.S. EPA, 2000; 1988). In this study, cattails (*Typha angustifolia*) were planted in each experimental unit at a density of 20 rhizomes/m^2. The macrophytes were watered with tap water until they were established. After plant acclimation, all plants were cut at 15 cm above the ground surface. Subsequently, Mn and Fe contaminated groundwater was fed into the experimental plots.

2.2. System operation and sample analysis

To meet the objectives of the study, two phases of works were conducted. In the first phase of the study, the effect of HRT on CW performance for Mn and Fe reduction was evaluated. When the initial phase of the study was complete, CW experimental units were again similarly established. The most appropriate HRT from the first phase of study was applied for CW operation in the next phase, in which efficiencies of the CW for Mn and Fe removal were investigated at various plant harvest intervals.

In the first phase of the study, shallow groundwater collected from a well close to the research area was continuously fed into the CW system at different flow rates for variable HRT of 12, 24 and 48 hours. The water level was maintained at 0.1 m above the soil surface so that each unit contained a liquid volume of 0.1 m3. Influent and effluent were collected frequently for each HRT experiment. Influent samples were taken from the feeding tank and effluent samples were collected from the outlet points of each plot. The samples were analyzed for Mn and Fe concentrations using spectrophotometer with limit of detention (LOD) of 0.0004 and 0.0015 mg/l for Mn and Fe analysis, respectively. Moreover, pH, Dissolved Oxygen (DO), Total Dissolved Solid (TDS) and Electrical Conductivity (EC) were also monitored onsite. The water samples were analyzed according to the Standard Methods for the Examination of Water and Wastewater (APHA, AWWA, WPCF, 1992). A CW experiment without plants was set up as control unit. Influent and effluent of the control unit were also collected and analyzed, similarly to those of the treatment units.

In the second phase of the study, the effect of plant harvest interval on the metal removal was investigated. Based on the result of the first phase of the study, each CW system was operated with a selected HRT and groundwater was continuously fed into the treatment units. Plant harvest was carried out at intervals of 4, 6 and 8 weeks. Before CW system start up, all plant shoots were cut at 20 cm above the soil surface. Throughout the experimental period, shoots were

Figure 1. Experimental units of the study

harvested and shoot samples within a 0.25 m^2 quadrate sampling plot were collected 2 times for each harvest interval. Root samples were also collected at the end of the operation. After wet weighing, plant samples were clipped and dried to constant weight at 70°C before dry weighing. The Relative Growth Rate (RGR) was calculated from the formula of

$$RGR = \frac{InW_2 - InW_1}{t_2 - t_1}$$

where W_1 and W_2 are dry biomass at the beginning (t_1) and at the end of the experimental period (t_2), respectively (Beadle, 1982). Some dried shoot and root tissues were analyzed for Mn and Fe accumulation. Similar to the first phase of the study, influent and effluent of CW units were sampled and analyzed.

2.3. Data analysis

Experimental data obtained from both phases of the study were analyzed to assess statistical differences in treatment efficiency between variables. The performance of each system was evaluated, based on metal concentrations, as a percentage removal of the pollutants. In the second phase of the study, biomass, Fe and Mn accumulation in cattails under different conditions were also analyzed. *T*-test, *F*-test and Duncan's Multiple Rank Test (DMRT) were used for statistical comparison at the *0.05* significance level.

3. Results and Discussion

3.1. Treatment performance of CWs at different HRTs

In the first phase of the study, groundwater with 1.03-5.32 mg/l of Mn and 0.57-19.46 mg/l of Fe was used. Average concentrations of 3.27 mg Mn /l and 5.21 mg Fe /l in groundwater were higher than the recommended maximum concentrations for crop production, which were determined at 0.20 mg/l for Mn and 5.0 mg/l for Fe (Ayers and Westcot, 1994). pH, DO, EC and TDS of the influent were 6.7-8.9, 2.6-3.6 mg/l, 203.0-249.0 μS/cm and 102.0-123.0 mg/l, respectively.

The groundwater was fed into the CW systems at 0.052-1.065 g/m^2/d and 0.028-3.891 g/m^2/d for Mn and Fe loading rates, respectively. When the system was operated at 12, 24 and 48 hours of HRT, average Mn loading rates were found to be 0.656, 0.331 and 0.164 g/m^2/d, respectively meanwhile average loading rates of Fe were 1.043, 0.521 and 0.261 g/m^2/d, respectively.

Table 1 illustrates the performance of the CW systems for reduction of Mn and Fe in groundwater at different HRTs. The efficiencies were 46.42-99.84 and 9.02-98.89% for decreasing of Mn and Fe concentrations, respectively. When in term of Area adjusted Removal Rate (ARR) was considered, reductions of Mn and Fe were 0.050-1.053 and 0.008-2.219 g/m^2/d, respectively. The CW systems showed significantly higher performance for both Fe and Mn removal comparing to those of unplanted units (control units) because plants can promote pollutant removal efficiency through physical process such as adsorption and filtration (Hares and Ward, 2004; Kadlec and Knight, 1996), chemical process such as precipitation (Kadlec and Knight, 1996; Matagi *et al.*, 1998) and biological process such as assimilation (Barley *et al.*, 2005; Demirezen and Aksoy, 2004; Groudeva *et al.*, 2001; Kadlec and Knight, 1996; Lu *et al.*, 2004; Peverly *et al.*, 1995; Soltan and Rashed, 2003; Weis and Weis, 2004). This result was supported by investigation of Cortes-Esquivel *et al.* (2012), Khan *et al.* (2009), Maine *et al.* (2006), Marchand *et al.* (2010) and Soda *et al.* (2012) that indicated important roles of macrophytes in treatment wetland for metal decontamination.

During operation period, it was found that the efficiency of the CW systems for Mn and Fe removal were quite steady as shown in Figs. 2 and 3, respectively. Comparing between tested conditions, the highest Mn concentration reduction appeared at 48 hours of HRT meanwhile Fe concentration reduction was not significantly different between HRTs. Increasing of HRT typically encourages contact time between pollutants and significant artificial wetland components that play a role in treatment processes. This procedure results in high performance of the wetland for heavy metal removal as found in Cortes-Esquivel *et al.* (2012). However, the CW system operated at 12 hours of HRT gave the highest performance for both Fe and Mn removal when the ARR was considered (Table 1).

As shown in Table 2, Mn and Fe concentrations in effluent were 0.005-0.897 and 0.027-2.236 mg/l, respectively. Average Mn concentration and Fe concentration in effluent of the CWs operated at different HRTs met water quality standard for irrigation (Ayers and Westcot, 1994). Similarly, Mn concentrations in effluent were in the range of the Thailand surface water quality standard type 3 (Mn ≤ 1 mg/l). This type of surface water is medium clean fresh water that is appropriate for (1) consumption after purification by ordinary treatment process and (2) agriculture (Department of Environmental Quality Promotion, 1994). Meanwhile, Fe was not determined in surface water quality standard. pH, DO, EC and TDS values of effluent were 6.5-10.2, 2.5-4.1 mg/l, 94.6-265.0 μS/cm and 66.8-227.0 mg/l, respectively. Comparing with pH of the influent, pH of the effluent were higher with the average effluent pH of 7.8 to 9.0.

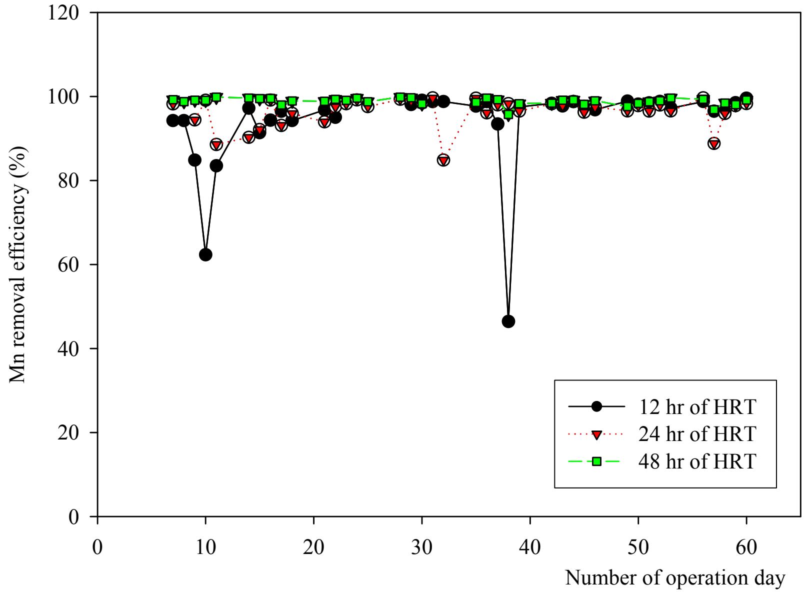

Figure 2. Mn removal efficiency of CWs operated at different HRT

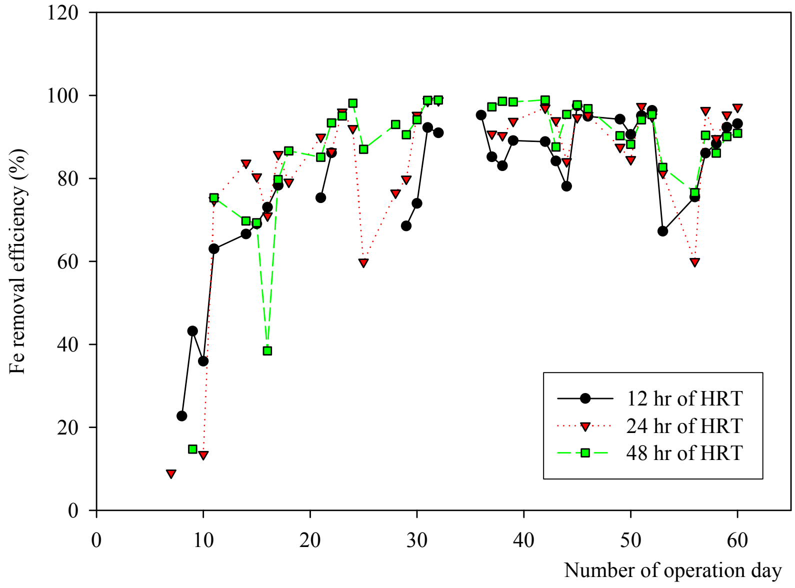

Figure 3. Fe removal efficiency of CWs operated at different HRT

Table 1. Performance of CWs for Fe and Mn removal at different HRTs.

HRT (hours)	Fe removal				Mn removal			
	Treatment efficiency (%)		AAR ($g/m^2/d$)		Treatment efficiency (%)		AAR ($g/m^2/d$)	
	CW unit	Control unit	CW unit	Control unit	CW unit	Control unit	CW unit	Control unit
12	79.21^{Aa} (33)	61.49^{Bb} (15)	0.801^{Aa} (33)	0.733^{Aa} (15)	93.98Ba (36)	70.26^{Bb} (18)	0.628^{Aa} (36)	0.483^{Ab} (20)
24	83.18^{Aa} (36)	$72.73A^{Ba}$ (16)	0.513^{Ba} (36)	0.190^{Bb} (16)	$96.44A^{Ba}$ (39)	70.98^{Bb} (9)	0.320^{Ba} (39)	0.160^{Bb} (9)
48	86.37^{Aa} (35)	89.62^{Aa} (10)	0.267Ca (35)	0.118^{Bb} (10)	98.82^{Aa} (38)	98.31^{Ab} (9)	0.165Ca (38)	0.139^{Ba} (9)

Note: Mean values in each column followed by the same letter (large letter) are not significantly different at $p \geq 0.05$.
Mean values in each row followed by the same letter (small letter) are not significantly different at $p \geq 0.05$.
Numbers in parenthesis are sample sizes.
AAR = Area adjusted removal rate.

This pH value was in the typical pH range of 6.5 to 9.2 reported by Ayers and Westcot (1994) and almost also in the range of 6.5 to 8.4 indicated by Bauder and Brock (2001) for irrigation water. In the CW systems, oxygen was added into treated groundwater through re-aeration and photosynthesis which consumes free CO_2 and increases pH value in water (Chaowanklang, 1991) as found in the effluent of this study. EC and TDS values in effluent, which were similar to those generally appeared in surface water, were suitable for irrigation. Meanwhile, Ayers and Westcot (1994) reported EC and TDS values of irrigation water were limited at 3,000 µS/cm and 2,000 mg/l, respectively. However, some limitation for irrigation use can occur when EC of water is more than 750 µS/cm (Bauder and Brock, 2001).

3.2. Treatment performance of CWs at different plant harvest intervals

As a result of the prior experiment, CW system operated at 12 hours of HRT illustrated the highest ARR for both Fe and Mn reduction meanwhile Fe and Mn concentrations in the effluent of that system were also in the range of the criteria of water quality for agricultural use. Furthermore, it is recognized that high volume of water is continuously required for irrigation including for paddy field. Then, the removal efficiency of CW system operated at 12 hours of HRT which provided high load of purified groundwater were evaluated in the second phase of study, which plants in the system were cut at various harvest intervals.

In the second phase of the study, Mn and Fe were fed into CW system at loading rates of 0.016-0.149 and 0.177-0.995 g/m2/day, respectively. Efficiencies of the system operated at 4, 6 and 8 weeks of plant harvest intervals were 75.63-100.00% for Mn removal and 48.58-99.40%, for Fe removal as depicted in Table 3, respectively. Average Mn and Fe removal efficiencies throughout the experimental period were not significant difference between various harvest intervals ($p \geq 0.05$). Nevertheless, most of experimental units showed statically increasing performance for both Mn and Fe reduction after the first plant harvest. These results supported the criteria for CW system maintenance that suggested appropriate plant harvest to keep performance of the system (Hosoi *et al*., 1998; Reddy and D'Angelo, 1990).

Mn and Fe removal rates were 0.016-0.149 and 0.006-0.916 g/m^2/d, respectively. The statistical analysis revealed Mn and Fe removal rates were considerable difference between various harvest intervals. The highest Mn and Fe removal rate was achieved in CWs operated at 4 weeks of the harvest intervals (Table 3). In addition to adsorption of Mn and Fe on surface of media and biota, absorption is also significant process for heavy metal removal. In CW system, heavy metals can be absorbed through plant root. Most of them are collected in vacuole whereas the remainders are transferred through xylem to plant stem. In this study, it was expected that re-growth of stem after plant harvest encouraged Mn and Fe absorption of the cattail. Mn and Fe concentrations in the effluent were found from non-detected (ND) level to 0.106 and 0.028-1.890 mg/l, respectively which were in the range of quality standard for irrigation water. Those in the effluent were not significantly different between various harvest intervals. Comparing to those before harvesting the plants, both Mn and Fe concentrations

Table 2. Characteristics of influent and effluent from the CWs operated at different HRTs.

Parameters	Units	Influent	Effluent		
			HRT 12 hours	HRT 24 hours	HRT 48 hours
pH	-	7.40±0.2^c (17)	9.02±0.1^a (36)	7.76±0.1^b (40)	7.98±0.1^b (40)
DO	mg/l	2.97±0.1^b (8)	3.41±0.1^a (20)	3.36±0.1^a (20)	3.35±0.1^a (20)
EC	µS/cm	218.3±2.6^a (17)	188.8±3.3^b (32)	211.5±4.6^a (40)	207.3±5.2^a (40)
TDS	mg/l	109.2±1.2^a (17)	94.6±1.8^b (32)	108.4±3.8^a (40)	108.3±2.8^a (40)
Fe	mg/l	5.21±0.7^a (40)	0.70±0.1^b (33)	0.58±0.1^b (36)	0.51±0.1^b (35)
Mn	mg/l	3.27±0.2^a (40)	0.15±0.0^b (36)	0.11±0.0^b (39)	0.04±0.0^c (38)

Note: Mean values ± SEM and sample size (n) in parenthesis are shown.
Mean values in each row followed by the same letter (small letter) are not significantly different at $p \geq 0.05$.

Table 3. Performance of CWs operated at different harvest intervals for Fe and Mn reduction and concentration of Fe and Mn in effluent

Parameters	Units	Harvest intervals		
		Every 4 weeks	Every 6 weeks	Every 8 weeks
Removal efficiency	%			
Mn removal efficiency				
- in first harvest period		92.0±1.5 (10)^{Ba}	92.6±1.2 (18)^{Ba}	95.2±1.5 (18)^{Ba}
- in second harvest period		99.8±0.1 (14)^{Aa}	100.0±0.0 (18)^{Aa}	100.0±0.0 (18)^{Aa}
- throughout the experiment		96.6±1.0 (24)^{a}	96.3±0.9 (36)^{a}	97.6±0.9 (36)^{a}
Fe removal efficiency				
- in first harvest period		81.1±3.2 (10)^{Ba}	80.1±3.0 (18)^{Ba}	80.5±2.6 (26)^{Aa}
- in second harvest period		90.6±1.6 (14)^{Aa}	89.0±2.1 (24)^{Aa}	87.5±2.2 (26)^{Aa}
- throughout the experiment		86.6±1.9 (24)^{a}	85.2±1.8 (42)^{a}	84.0±1.8 (52)^{a}
Removal rate	g/m^2/d			
Mn removal rate				
- in first harvest period		0.108±0.00 (10)^{Aa}	0.099±0.00 (18)^{Aa}	0.092±0.01 (18)^{Aa}
- in second harvest period		0.080±0.01 (14)^{Ba}	0.042±0.00 (18)^{Bb}	0.044±0.01 (18)^{Bb}
- throughout the experiment		0.092±0.00 (24)^{a}	0.070±0.01 (36)^{b}	0.068±0.01 (36)^{b}
Fe removal rate				
- in first harvest period		0.413±0.10(10)^{Aa}	0.071±0.01(18)^{Ab}	0.067±0.01(26)^{Ab}
- in second harvest period		0.361±0.05(14)^{Ab}	0.044±0.01(24)^{Ba}	0.067±0.01(26)^{Aa}
- throughout the experiment		0.383±0.05(24)^{a}	0.056±0.01(42)^{b}	0.067±0.01(52)^{b}
Effluent concentration	mg/l			
Mn concentration				
- in first harvest period		0.0494±0.01(10)^{Aa}	0.0414±0.01(18)^{Aab}	0.0243±0.01(18)^{Ab}
- in second harvest period		0.0007±0.00(14)^{Ba}	0.0001±0.00(18)^{Ba}	0.0000±0.00(18)^{Ba}
- throughout the experiment		0.0210±0.01(24)^{a}	0.0208±0.00(36)^{a}	0.0122±0.00(36)^{a}
Fe concentration				
- in first harvest period		0.351±0.05(10)^{Aa}	0.354±0.04 (18)^{Aa}	0.337±0.03 (26)^{Aa}
- in second harvest period		0.174±0.03(14)^{Ba}	0.221±0.03 (24)^{Ba}	0.335±0.07 (26)^{Aa}
- throughout the experiment		0.248±0.03(24)^{a}	0.278±0.03 (42)^{a}	0.336±0.04 (52)^{a}

Note: Mean values ± SEM and sample size (n) in parenthesis are shown.
Mean values in each column followed by the same letter (capital letter) are not significantly different at $p \geq 0.05$.
Mean values in each row followed by the same letter (small letter) are not significantly different at $p \geq 0.05$.

in the effluent of almost experimental units after the first plant harvest became significantly lower, relating to the removal efficiency (Table 3).

3.3. Plant growth and metal accumulation

Biomass production and RGR of cattails in the CWs are shown in Table 4. Dry weights of cattail shoots cut from CWs operated at 4, 6 and 8 weeks of the harvest intervals were 158.4-307.2, 267.2-676.8 and 216.0-536.0 g/m^2, respectively for the first harvest and 217.6-1,660.8, 428.8-643.2 and 459.2-852.8 g/m^2, respectively for the second harvest. Additionally, dry weights of underground tissue harvested from those at the end of the operation were 600.0-1,908.8, 606.4-1,598.4 and 475.2-2,032.0 g/m^2, respectively. The first harvest, RGRs of cattails in CWs operated at 4, 6 and 8 weeks were 0.181-0.205, 0.136-0.159 and 0.096-0.112 day^{-1}, respectively whereas RGRs of those were 0.192-0.265, 0.148-0.158 and 0.109-0.121 day^{-1}, respectively for the second harvest.

The results revealed that cattails in the CW systems could re-growth after the harvest. In all tested systems, aboveground biomass as well as RGR of

Table 4. Biomass production and RGR of cattails in CWs operated at different plant harvest intervals

Parameters	Units	Harvest intervals		
		Every 4 weeks	Every 6 weeks	Every 8 weeks
Dry weight	g/m^2			
Aboveground tissue				
- first harvest		219.5 ± 24.4^{Ab}	389.3 ± 62.8^{Aa}	388.3 ± 43.7^{Ba}
- second harvest		581.9 ± 226.4^{Aa}	530.1 ± 33.0^{Aa}	687.5 ± 67.2^{Aa}
Underground tissue		925.3 ± 200.6^{a}	976.3 ± 147.8^{a}	982.9 ± 257.0^{a}
RGR	day^{-1}			
- first harvest		0.192 ± 0.004^{Aa}	0.144 ± 0.004^{Ab}	0.106 ± 0.002^{Bc}
- second harvest		0.217 ± 0.012^{Aa}	0.153 ± 0.002^{Ab}	0.116 ± 0.002^{Ac}

Note: Mean values ± SEM at sample size (n) = 6 are shown.
Mean values in each column followed by the same letter (capital letter) are not significantly different at $p \geq 0.05$.
Mean values in each row followed by the same letter (small letter) are not significantly different at $p \geq 0.05$.

cattails in the second harvest were higher than those in the first harvest as shown in Table 4. Comparing between various harvest intervals, the highest RGR of cattails was obtained at 4 weeks of the harvest intervals for both harvest times. However, the lowest dry mass product was found in the first harvest of this test interval may due to the shortest period for the production. For underground tissue, there was no difference for dry mass production between various harvest intervals.

Regarding Mn and Fe accumulation in plant, average Mn and Fe concentrations in aboveground and underground tissues are revealed in Table 5. Similar to Mn concentrations in cattail shoots and roots, most of Fe concentrations in cattail tissues were similar in all variable harvest intervals. Nevertheless, Fe concentrations were significant difference between shoots achieved from the first and second harvest for all tested harvest intervals. Meanwhile, statistical difference was also found between Fe concentrations in roots obtained from CWs operated at different harvest intervals.

Mn accumulation rates were in the ranges of 0.32-8.25, 0.11-4.34 and 0.04-3.39 $mg/m^2/d$ for shoots that were cut at 4, 6 and 8 weeks of the harvest interval, respectively whereas Fe accumulation rates were 0.12-6.61, 0.03-72.50 and 0.04-164.27 $mg/m^2/d$ for those, respectively. As shown in Table 5, in all the harvest intervals, Mn accumulation rates of shoots were similar as well as roots. Furthermore, those of shoots were similar both in the first and second harvest. However, statistical analysis illustrated that Fe accumulation rates of shoots from the second harvest were higher except those at 4 weeks of the interval. This result confirmed that re-growth of cattails could stimulate Fe accumulation. Baldantoni *et al.* (2009) reported that metals were efficiently removed by immobilization in rhizosphere and stored in belowground biomass. Barley *et al.* (2005), Groudeva *et al.* (2001) and Peverly *et al.* (1995) also informed that wetland plant root was a main structure that absorbed and accumulated heavy metal. It was found in this study that cattail roots obviously exhibited higher Mn and Fe accumulation rates than those of shoots. This indicates that a majority of metals was trapped in roots. This was confirmed by Shanker *et al.* (2005) that noted that sequestration of metals in vacuoles of root cells might be a reason of poor metal translocation from roots to shoots.

4. Conclusion

Cattail constructed wetland exhibited prominent removal performance for Fe and Mn in groundwater although the wetland was operated at short tested period of HRTs. Besides, in this study, CW system with the shortest HRT discharged high hydraulic volume of effluent with quality in the criteria of irrigation use. This was due to several metals removal processes taken place in CW system, for instance, filtration, sedimentation, precipitation, sorption including plant uptake. As found in this research, plant accumulation could immobilize both Fe and Mn which were presented in plant tissues. Although, almost of metal concentrations and metal accumulation rates of shoots were not different between the tested harvest intervals, the results showed that those of shoots obviously increased after the harvesting. Therefore, plant harvest was important for maintaining the removal performance f CW for the reason that plant re-growth could encourage the metal assimilation.

Table 5. Mn and Fe concentrations of cattail tissue and Mn and Fe accumulation rate of cattails in CWs operated at different plant harvest intervals

Parameters	Units	Harvest intervals		
		Every 4 weeks	Every 6 weeks	Every 8 weeks
Concentrations in tissue	mg/kg			
Mn concentrations				
Aboveground tissue				
- first harvest		265.6±27.1^{Aa}	245.1±42.6^{Aa}	186.8±30.4^{Aa}
- second harvest		165.8±20.4^{Bb}	254.4±23.9^{Aa}	241.5±20.7^{Aa}
Underground tissue		130.2±14.6^{a}	211.4±39.6^{a}	242.6±127.0^{a}
Fe concentrations				
Aboveground tissue				
- first harvest		76.6±5.9^{Ba}	106.6±13.4^{Ba}	69.6±9.1^{Ba}
- second harvest		801.8±242.8^{Aa}	1,600.4±537.0^{Aa}	3,122.3±986.8^{Aa}
Underground tissue		16,951.9±1,792.2^{b}	19,452.2±1,357.9^{b}	24,857.3±2,014.4^{a}
Accumulation rate	mg/m^2/d			
Mn accumulation rate				
Aboveground tissue				
- first harvest		1.17±0.26^{Aa}	1.43±0.42^{Aa}	0.84±0.23^{Aa}
- second harvest		1.61±0.62^{Aa}	1.50±0.21^{Aa}	1.49±0.21^{Aa}
Underground tissue		4.58±1.43^{a}	4.44±0.40^{a}	5.19±3.60^{a}
Fe accumulation rate				
Aboveground tissue				
- first harvest		0.29±0.05^{Aa}	0.48±0.11^{Ba}	0.26±0.06^{Ba}
- second harvest		0.96±0.52^{Aa}	15.89±6.40^{Aa}	41.40±14.93^{Aa}
Underground tissue		586.94±173.37^{a}	458.12±77.53^{a}	900.94±254.37^{a}

Note: Mean values ± SEM are shown.
Mean values in each column followed by the same letter (capital letter) are not significantly different at $p \geq 0.05$.
Mean values in each row followed by the same letter (small letter) are not significantly different at $p \geq 0.05$.
Sample size (n) of aboveground tissue and underground tissue are 12 and 6, respectively.

Acknowledgements

Sincere appreciation is extended to the Office of the Higher Education Commission (HEC) and The Thailand Research Fund (TRF) for financial support. The author gratefully acknowledges Naresuan University for providing facilities to this study and Professor Dr. Michael Barbetti and Dr. Sugunya Utida for their kindly help and support.

References

APHA. Standard methods for the examination of water and wastewater. 18th ed. APHA, AWWA, WPCF, Washington DC, USA. 1992.

Ayers RS, Westcot DW. Water quality for agriculture. Food and Agriculture Organization of the United Nations, Rome. 1994.

Baldantoni D, Ligrone R, Alfani A. Macro-and trace-element concentrations in leaves and root of *Phragmites australis* in a volcanic lake in Southern Italy. Journal of Geochemical Exploration 2009; 101(2): 166-74.

Barley RW, Hutton C, Brown MME, Cusworth JE, Hamilton TJ. Trends in biomass and metal sequestration associated with reeds and algae at Wheal Jane Biorem pilot passive treatment plant. Science of the Total Environment 2005; 345(1-3): 279-86.

Bauder JW, Brock TA. Irrigation water quality, soil amendment, and crop effects on sodium leaching. Arid Land Research and Management 2001; 15(2): 101-13.

Beadle CL. Plant growth analysis. *In*: Techniques in bio-productivity and photosynthesis (*Eds*: Coombs J, Hall DO). Pergamon Press., New York, USA. 1982; 20-24.

Becker M, Asch F. Iron toxicity in rice - conditions and management concepts. Journal of Plant Nutrition and Soil Science 2005; 168(4): 558-73.

Chaowanklang P. Water quality for aquaculture. Physics Center Press Limited., Bangkok. 1991.

Cortes-Esquivel JA, Giácoman-Vallejos G, Barceló-Quintal ID, Méndez-Novelo R, Ponce-Caballero MC. Heavy metals removal from swine wastewater using constructed wetlands with horizontal sub-surface flow. Journal of Environmental Protection 2012; 3(s1): 871-77.

Demirezen D, Aksoy A. Accumulation of heavy metal in *Typha angustifolia* (L.) and *Potamogeton pectinatus* (L.) living in Sultan Marsh (Kayseri, Turkey). Chemosphere 2004; 56(7): 685-96.

Department of Environmental Quality Promotion. Enhancement and conservation of national environmental quality Act, B.E. 2535 and related law. The Royal Government Gazette, Vol. 111, Part 16, dated February 24, B.E. 2537. Bangkok. 1994.

Groudeva VI, Groudev SN, Doycheva AS. Bioremediation of waters contaminated with crude oil and toxic heavy metals. International Journal of Mineral Processing 2001; 62(1-4): 293-99.

Hares RJ, Ward NI. Sediment accumulation in newly constructed vegetative treatment facilities along a new major road. Science of the Total Environment 2004; 334-335: 473-79.

Hosoi Y, Kido Y, Miki M, Sumida M. Field examination on reed growth, harvest and regeneration for nutrient removal. Water Science and Technology 1998; 38(1): 351-59.

Kadlec RH, Knight RL. Treatment wetlands. Lewis Publishers., Florida. 1996.

Khan S, Ahmad I, Shah MT, Rehman S, Khaliq A. Use of constructed wetland for the removal of heavy metals from industrial wastewater. Journal of Environmental Management 2009; 90(11): 3451-57.

Kröpfelová L, Vymazal J, Švehla J, Štíchová J. Removal of trace elements in three horizontal sub-surface flow constructed wetlands in the Czech Republic. Environmental Pollution 2009; 157(4): 1186-94.

Lesley B, Daniel H, Paul Y. Iron and manganese removal in wetland treatment system: Rates, processes and implications for management. Science of the Total Environment 2008; 394(1): 1-8.

Lu X, Kruatrachue M, Pokethitiyook P, Homyok K. Removal of Cadmium and Zinc by Water Hyacinth, *Eichhornia crassipes*. ScienceAsia 2004; 30: 93-103.

Maine MA, Suñe N, Hadad H, Sánchez G, Bonetto C. Nutrient and metal removal in a constructed wetland for wastewater treatment from a metallurgic industry. Ecological Engineering 2006; 26(4): 341-47.

Marchand L, Mench M, Jacob DL, Otte ML. Metal and metalloid removal in constructed wetlands, with emphasis on the importance of plants and standardized measurements: A review. Environmental Pollution 2010; 158(12): 3447-61.

Matagi SV, Swai D, Mugabe R. A review of heavy metal removal mechanisms in wetlands. African Journal of Tropical Hydrobiology and Fisheries 1998; 8: 23-35.

Nelson LE. Tolerances of 20 rice cultivars to excess Al and Mn. Agronomy Journal 1983; 75(1): 134-38.

Peverly JH, Surface JM, Wang T. Growth and trace metal absorption by *Phragmites australis* in wetlands constructed for landfill leachate treatment. Ecological Engineering 1995; 5(1): 21-35.

Reddy KR, D'Angelo EM. Biomass yield and nutrient removal by water hyacinth (*Eichhornia crassipes*) as influenced by harvesting frequency. Biomass 1990; 21(1): 27-42.

Sahrawat KL. Iron toxicity in wetland rice and the role of other nutrients. Journal of Plant Nutrition 2005; 27(8): 1471-504.

Shanker AK, Cervantes C, Loza-Tavera H, Avudainayagam S. Chromium toxicity in plants. Environment International 2005; 31(5): 739-53.

Soda S, Hamada T, Yamaoka Y, Ike M, Nakazato H, Saeki Y, Kasamatsu T, Sakurai Y. Constructed wetlands for advanced treatment of wastewater with a complex matrix from a metal-processing plant: Bioconcentration and translocation factors of various metals in *Acorus gramineus* and *Cyperus alternifolius*. Ecological Engineering 2012; 39: 63-70.

Soltan ME, Rashed MN. Laboratory study on the survival of water hyacinth under several conditions of heavy metal concentrations. Advances in Environmental Research 2003; 7(2): 321-34.

U.S. EPA. Constructed wetlands treatment of municipal wastewater. Office of Research and Developmen, Cincinnati, Ohio, USA. 2000.

U.S. EPA. A citize's guide to phytoremediation. Technology Innovation Office., Washington DC, USA. 1988.

Weis JS, Weis P. Metal uptake, transport and release by wetland plants: implications for phytoremediation and restoration. Environment International 2004; 30(5): 685-700.

Yeh TY, Chou CC, Pan CT. Heavy metal removal within pilot-scale constructed wetlands receiving river water contaminated by confined swine operations. Desalination 2009; 249(1): 368-73.

Yimprae P. Accumulation of iron and manganese from groundwater into paddy soil and rice. Thesis of Master of Science, Naresuan University, Thailand. 2004.

Received 17 April 2014
Accepted 22 May 2014

Correspondence to
Dr.Pantip Klomjek
Faculty of Agriculture, Natural Resources and Environment,
Naresuan University,
Phitsanulok, 65000,
Thailand
Tel: +66-5596-2755
Fax: +66-5596-2750
Email: pantipk@nu.ac.th