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Characteristics of contaminants in water and sediment of a constructed wetland treating piggery wastewater effluent

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Abstract

Constructed wetland (CW) is the preferred means of controlling water quality because of its natural treatment mechanisms and function as a secondary or tertiary treatment unit. CW is increasingly applied in Korea for secondary effluent of livestock wastewater treatment. This study was conducted to recognize the characteristics of contaminants in the accumulated sediment at the bottom soil layer and to reduce the phosphorus release from sediments of the free water surface CW for the treatment of secondary piggery wastewater effluent from a livestock wastewater treatment facility. The results revealed that the dominant phosphorus existence types at near the inlet of the CW were non-apatite phosphorus (59%) and residual phosphorus (32%) suggesting that most of the particles of the influent are made up of inorganic materials and dead cells. Sediment accumulation is important when determining the long-term maintenance requirements over the lifetime of CW. Continuous monitoring will be performed for a further assessment of the CW system and design.

Key words: constructed free water surface wetland; piggery wastewater; phosphorus type; secondary wastewater effluent; sediment

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Introduction

Livestock wastewater is classified as high-organic-loading and high-nutrient-content wastewater. The Ministry of Environment (MOE) in Korea has proposed various measures in reducing the pollutant loading from livestock wastewater, particularly piggery wastewater, to improve not only the quality of water bodies but also to protect the human health. However, processed wastewater continues to contain high levels of contaminants subsequent to treatment. Therefore, effluent introduced to agricultural lands or rivers can result in pollutant accumulation in the soil and/or groundwater. Recently, wetlands are increasingly constructed worldwide as a low-cost environmentally friendly means to improve the quality of wastewater, including secondary wastewater treatment facility effluent, mine wastes, stormwater, and nonpoint source pollution (Moshiri, 1993; Vymazal et al., 1998). According to Brix (1993), constructed wetland (CW) is suitable for wastewater treatment, especially for post treatment, because the wetland vegetation and organisms in these environments can adapt to the wastewater inflow and utilize the various organic and inorganic pollutants during metabolic and other life processes. In Korea, several studies regarding the application of CW for the treatment of livestock wastewater and sewage were started since 2000 (Park et al., 2004; Seo et al., 2009). The MOE decided in 2007 to apply CW to treat secondary livestock effluent.

The complex and integrated environment of wetlands provides a great number of mechanisms to remove contaminants from water, including physical and chemical processes (adsorption, precipitation, sedimentation, etc.) as well as biological processes (bacterial transformation and assimilation through aquatic vegetation) (Moshiri, 1993). Among these mechanisms, the most important treatment process common to all wetland systems is the physical settling of suspended particulate matters such as silt or clay, or fine particles of organic and inorganic matters. These pollutants may be absorbed into the sediments that accumulate on the bottom of the wetland. Moreover, sedimentary material is involved in the most significant internal process in nutrient-rich treatment wetlands. The substantial supply of nutrients assures a wide variety of the production of transportable organisms and associated dead organic material. Such wetlands are characterized by a high water chlorophyll content and high sediment accumulation.

Sediments in CW may accumulate over long periods and can act as new pollutant sources to the overlying water (Lijklema et al., 1993). They may uptake or release contaminants when environmental conditions such as pH, temperature and dissolved oxygen (DO) concentration in the water change (Golterman, 1977; Lijklema, 1977).

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Sediment resuspension or pollutant desorption may be important sources of pollutants to the water column, and this potential release is a growing concern. The characteristics of sediments, as well as the overlying water quality, will affect release rate (Xi et al., 2007). Numerous studies have reported the characteristics of accumulated sediment in CW, such as phosphorus storage, distribution, and the associations of the metals in contaminated materials (White et al., 2000; Dunne et al., 2005; Maine et al., 2007). Phosphorus accumulation, distribution and release rates from sediments were also reported (Furumai et al., 1989; Kim and Choi, 1996; Kim et al., 2003). However, research on the subject of the release of phosphorus along with type of release from wetland sediments when environmental conditions change remains nonexistent. Due to the effects of the physico-chemical and environmental conditions on the interface between the water and sediments, the proportion of phosphorus compounds could be modified and phosphorus compounds that have already accumulated within the sediments could be partially released. As permanent phosphorus exchange takes place within this interface, over time the sediment can act as an internal source of phosphorus for the overlying water (Lijklema, 1986). Therefore, to achieve water quality goals, it will be necessary to reduce phosphorus sources further in CW. Reducing or eliminating phosphorus release from sediments may also be required.

This study focused on free water surface (FWS) CW and its role in removing sediment from treated secondary piggery wastewater effluent. This is important when determining the long-term maintenance requirements over the lifetime of the CW. Therefore, this study was conducted to recognize the characteristics of the contaminants in the accumulated sediment at the bottom soil layer of the FWS CW and to reduce phosphorus release from sediments at varying dissolved oxygen (DO) levels, pH values, temperatures, and other physical conditions.

1 Materials and methods

1.1 Site description

The FWS CW utilized for this study is located near the Geum River in Nonsan City, South Chungcheong Province, Korea. It was built in 2007 by the MOE and put into operation in September, 2008. Influent into the CW flows both from secondary piggery wastewater effluent treated from a livestock wastewater treatment facility during dry days and stormwater runoff from a livestock landuse area during wet seasons. The site has contaminated with organic matters, nutrients and pollutants such as livestock feed and animal droppings, particularly. The facility area of the CW is 4492 m^2 treating a catchment area of 110,000 m^2 which is mostly paved.

1.2 Constructed wetland design and characteristics

Figure 1 shows the composition of the CW and the sampling points for the water and sediment. The CW is composed of six cells (Table 1). The treatment mechanisms employed in the CW are sedimentation of particulates in cell 1, aeration in cell 2, and sedimentation of organics in the subsequent cells 3 to 6 in addition to treatment by vegetation. The characteristics of the CW are presented in Table 1 and the detailed information of the plant species in the CW is given in Table 2. Wetland plants were selected on the basis of their characteristics, such as, they grow quickly, were capable of removing contaminants and have high tolerance towards toxicities. They represented the dominant source of treatment due to their direct uptake and sequestering of pollutants. A variety of native plant seedling were implanted and cultivated on each cell.

1.3 Sampling and analysis of sediments and waters

Water samples were collected at six sampling points (the inlets of cell 1, cell 2, cell 4, cell 5, cell 6, and the outlet) along the hydrologic path in the CW from October 2008 to August 2009. Disturbed and undisturbed sediment samples were collected during the winter, spring and summer. The

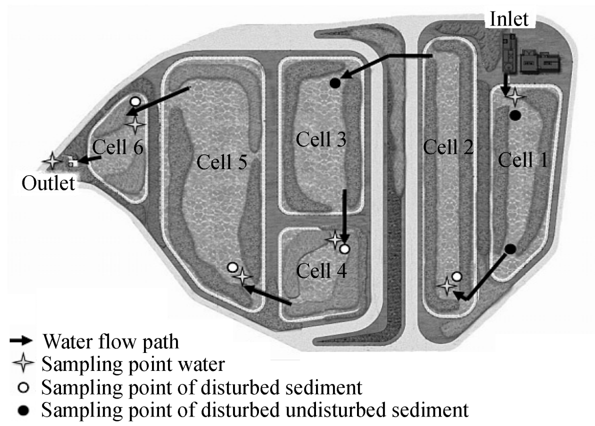

Fig. 1 Composition of the free surface constructed wetland (FWS CW) and the sampling points for the water and sediment.

Table 1 Specification of the constructed wetland

Cell No.	Function	Surface area (m^2)	Storage volume (m^3)	Water depth (cm)	HRT for design flow (hr)	HRT for peak flow (hr)
Cell 1	Settling basin	560	453	80.9	5.5	1.6
Cell 2	Aeration pond	776	565	72.8	6.8	2.0
Cell 3	Deep marsh	805	810	100.6	9.8	2.9
Cell 4	Shallow marsh	527	280	53.1	3.4	1.0
Cell 5	Deep marsh	1474	1626	110.3	19.6	5.8
Cell 6	Settling basin	350	272	77.7	3.3	1.0
Total		4492	4006		48.4	14.3

HRT: hydraulic retention time.

Table 2 Dominant plant species planted in the constructed wetland

Plant	Plants number	Cultivated cell
Phragmites communis	23,400	Cells 1, 2, 3, 5
Typha angustata	2800	Cells 3, 5
Miscanthus sacchariflorus	800	Cell 4
Phragmites japonica	4100	Cell 4
Nelumbo nucifera	1800	Cell 6
Eichhornia crassipes	–	Cell 6

"–" data are not available.

sampling points of sediment were chosen from two points (the inlet and outlet) selected in cell 1 and the inlet in cell 3 for undisturbed sediment and seven points (the inlet of cell 1 to cell 6 and the outlet of cell 1) for disturbed sediment, as shown in Fig. 1. Disturbed sediment samples were collected by a grab sampler, and undisturbed sediment was manually collected at each point using an acryl tube that was 5 cm in diameter and 50 cm long. Undisturbed sediment samples were separated to determine the pollutant amount in soil liner (SL) and accumulated sediment (AS). The depth was measured at each sample. Water and sediment samples were transported to the laboratory after collection for analysis. Parameters such as DO, pH, conductivity and temperature were measured in the field with portable meters. The water samples were analyzed for total suspended solids (TSS), turbidity, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total nitrogen (TN), total Kjeldahl nitrogen (TKN), ammonium nitrogen (NH_4-N), total phosphorus (TP) and phosphate (PO_4-P) according to American Society for Testing and Materials (ASTM) standard methods. The analyses of ignition loss, COD, TN and TP were performed to determine the chemical characteristics of the disturbed and undisturbed sediments.

1.4 Analysis of phosphorus types

Phosphorus types were determined using the procedure of Hieltjes and Lijklema (1980), which was used to analyze the concentrations of TP and the phosphorus fraction in sediments. This procedure successively extracts phosphorus from sediments using different solvents and conditions (Williams et al., 1980). Phosphorus was first extracted using 0.1 g of dried sediment with 20 mol/L of NH_4Cl at pH 7 (2 hr). This procedure removes loosely associated phosphorus, known as adsorbed-P (Ads-P) or NH_4Cl extractable P. The sediment residue from this extraction was subsequently extracted with 2 mol/L of NaOH (17 hr). Phosphorus precipitated with metal ions is known as non-apatite-P (NAI-P) or NaOH-P. The residual was extracted next with 10 mol/L of HCl (17 hr); it is termed apatite-P (A-P) or HCl extractable P. The remaining phosphorus is known as residual-P (R-P) or organic-P. It calculated according to Hieltjes and Lijklema (1980) as the difference between the TP and inorganic phosphorus (the sum of the Ads-P, NAI-P and A-P fractions).

2 Results and discussion

2.1 Characteristics of influent wastewater to the constructed wetland

Table 3 provides statistical summaries of the influent pollutant concentrations from the treated piggery wastewater to the CW. The mean concentrations of pH, DO and TSS are 7.9 ± 0.6, (4.2 ± 2.4) mg/L, and (62.2 ± 25.8) mg/L, respectively, while the mean concentrations of BOD, COD, TN and TP are (68.7 ± 37.2) mg/L, (137.7 ± 61.4) mg/L, (146.2 ± 46.7) mg/L, and (5.5 ± 2.1) mg/L, respectively. Generally, raw piggery wastewater in Korea contains 11,533 mg/L of BOD, 21,894 mg/L of COD, 2255 mg/L of TN and 415 mg/L of TP. When biologically treating wastewater, it is usually stated that the ratio of COD:TN:TP in the wastewater to be treated should be approximately 100:5:1 (MOE, 2004). The ratio of organics, particularly COD and BOD, and nutrients such as TN and TP concentrations of the influent is important to determine the biological activity of microorganisms, especially their growth aspect. If the proportion is unbalance, the microorganisms would not be able to treat the influent. Compared the corresponding proportions of organics and nutrients from different types of wastewater as shown in Table 4, it can be observed that the average organic content (BOD and COD) is low whereas the nutrients (TN and TP) are greater than necessary. If the organics are not sufficient or below the optimum ratio with the nutrients, it would be difficult to biologically treat the wastewater; especially

Table 3 Characteristics of influent concentrations to the CW (n = 16)

Parameters	Minimum	Maximum	Mean ± SD	95% confidence interval
pH	6.4	8.8	7.9 ± 0.6	7.6–8.3
DO (mg/L)	0.6	10.3	4.2 ± 2.4	2.9–5.5
BOD (mg/L)	16.1	131.1	68.7 ± 37.2	48.9–88.6
COD (mg/L)	36.0	232.3	137.7 ± 61.4	104.9–170.4
TSS (mg/L)	24.0	104.0	62.2 ± 25.8	48.5–76.0
Turbidity (NTU)	9.6	66.9	29.0 ± 17.4	19.7–38.3
TN (mg/L)	87.9	230.5	146.2 ± 46.7	121.3–171.1
NH_4-N (mg/L)	11.5	73.9	44.5 ± 18.4	34.6–54.3
TKN (mg/L)	52.4	117.3	83.0 ± 20.0	72.3–93.7
NO_3-N (mg/L)	3.1	13.0	9.4 ± 2.9	7.9–11.0
TP (mg/L)	1.9	9.5	5.5 ± 2.1	4.4–6.6
PO_4-P (mg/L)	0.2	4.7	1.5 ± 1.1	0.9–2.1

DO: dissolved oxygen; BOD: biochemical oxygen demand; COD: chemical oxygen demand; TSS: total suspended solids; TN: total nitrogen; TKN: total Kjeldahl nitrogen; TP: total phosphorus.

when the TN and TP concentrations were extremely high. This would probably lead to a low treatment efficiency of the CW.

2.2 Water quality changes for each cell

Figure 2 describes the average concentration trends of the specific constituents in each set of cells for the entire monitoring period. The average COD, TN, and TP concentrations decreased somewhat along the cells from the influent to the effluent, except for the DO concentration, which appeared to peak at cell 5. This is attributable to the sedimentation and aeration treatment from the prior cells and to algae photosynthesis in the cell itself. It was observed that most of the algae bloomed at the deep marsh of cell 5, especially during the spring. Algae are ubiquitous in wet habitats, which inevitably become components of FWS systems. While algae are a major component in certain treatment systems, the treatment performance of FWS CW can be affected significantly. The presence of open, unshaded water near the outlet of a constructed wetland typically promotes seasonal blooms of phytoplanktonic algal species, which results in elevated concentrations of suspended solids and particulate nutrient forms in the effluent (US EPA, 1999). Due to this phenomenon, the mean concentration of the TSS is lowest between the influent of cell 1 to cell 4 and highest between the influent of cell 4 to cell 6.

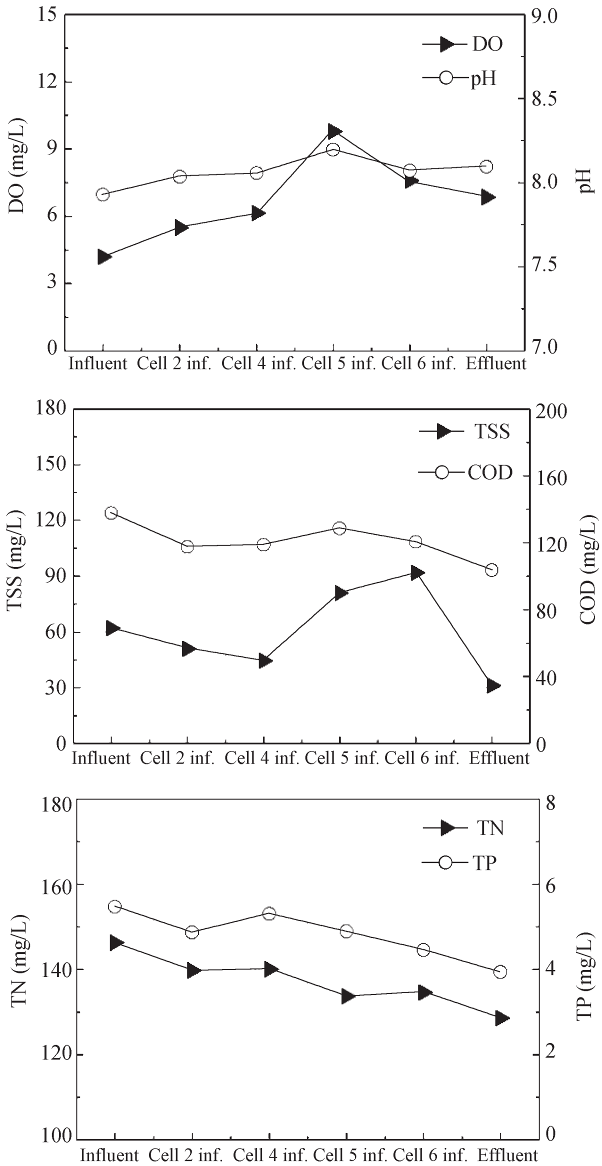

Fig. 2 Average concentrations of specific constituents for each set of cells in the CW between October 2008 and August 2009.

2.3 Sediment accumulation in cells

Undisturbed sediment samples were used to determine the pollutant amount of SL and AS at the bottom soil layer and measured depth at each sample (Table 5). The findings show that the particulate materials were precipitated at cells 1 and 3, as these cells act as a sedimentation basin in the CW. The sediment accumulation was low after July 2, 2009 due to the dredging that took place at that time. The differences in the sediment characteristics between cells 1 and 3 will be discussed later.

2.4 Chemical characteristics of undisturbed sediments

The chemical characteristics of the undisturbed sediments at each depth are presented in Table 6. The results show that the average concentration in AS from cell 1 to cell 3 decreased from 33,856 to 18,485 mg/kg for COD, from 1259 to 724 mg/kg for TP and from 1551 to 1206 mg/kg for TN. The amounts of organic matter and nutrients in AS are relatively high in cell 1 (first sedimentation basin) because the main mechanism of pollutant removal in the CW is sedimentation. These pollutants may be transferred from the water column to the sediment layer via biochemical and physical reactions such as ion exchange, adsorption and precipitation if these reactions continue over long periods. The difference in this concentration may represent the change in sediment pollutant concentrations in the wetland system over time, but may also be caused by the removal mechanisms present in the system.

2.5 Phosphorus type in undisturbed sediments

The largest type of phosphorus storage in a wetland is typically associated with the wetland soil and sediments. Phosphorus compounds are further removed by sorption to soils and by plant uptake (Brix, 1993). Phosphorus bound to metal oxides, mainly Fe and Al, is represented as NAI-P. The concentration of the NAI-P fraction can be used for the

Table 4 Ratio of organics and nutrients from different types of wastewater

Wastewater	Reference	BOD:TN:TP	COD:TN:TP	TN:TP
Raw livestock wastewater	MOE, 2004	28:5:1	53:5:1	5
Municipal wastewater (separate sewer system)	MOE, 2001	28:7:1	–	7
Influent wastewater to CW	This study (annual average)	13:29:1	28:29:1	29

"–" data are not available.

Table 5 Depth of each sediment in FWS CW (cm)

Monitoring date (mm/dd/yyyy)	Cell 1 inlet		Cell 1 outlet		Cell 2 inlet		Cell 3 inlet		Cell 4 inlet		Cell 5 inlet		Cell 6 inlet	
	SL	AS	SL	AS	SL	AS	SL	AS	SL	AS	SL	AS	SL	AS
02/05/2009	4.5	2.5	5	3.5	–	–	6.5	5	–	–	–	–	–	–
03/09/2009	6	3	4.4	5.6	–	–	4.4	4.8	–	–	–	–	–	–
05/11/2009	9	11	7	5	–	–	13.5	0.5	–	–	–	–	–	–
07/02/2009	6	14	3	12	7	9	13	2	17	1	15	1	17	2
08/25/2009	8	5	6	3	–	–	7	3	–	–	–	–	–	–

SL: soil liner; AS: accumulated sediment.
"–" data are not available.

Table 6 Average pollutant concentrations of undisturbed sediment at each depth

Parameter	Cell 1 inlet		Cell 1 outlet		Cell 3 inlet	
	SL	AS	SL	AS	SL	AS
Ignition loss (%)	5.5	5.5	6.5	5.9	4.2	5.2
COD (mg/kg)	30216	33856	26030	31630	21022	18485
TP (mg/kg)	642	1259	1109	1221	857	724
TN (mg/kg)	1178	1551	1196	1373	1043	1206

Table 7 Average concentrations for each phosphorus existence type of the undisturbed sediment

Phosphorus existence type	Concentration (mg/kg, %)					
	Cell 1 inlet		Cell 1 outlet		Cell 3 inlet	
	SL	AS	SL	AS	SL	AS
TP	642 (100)	1259 (100)	1109 (100)	1221 (100)	857 (100)	724 (100)
Ads-P	12 (2)	113 (9)	10 (1)	30 (2)	14 (2)	17 (2)
NAI-P	283 (44)	823 (65)	232 (21)	648 (53)	191 (22)	284 (39)
A-P	16 (2)	39 (3)	13 (1)	37 (3)	14 (2)	5 (1)
R-P	330 (51)	284 (23)	854 (77)	506 (41)	637 (74)	418 (58)

Data are expressed by average concentration in mg/kg and the corresponding percentage in parenthesis.

estimation of both the short-term and long-term available phosphorus in sediments and to measure the available algal phosphorus. The phosphorus fraction that is assumed to consist mainly of A-P is represented as HCl-P. The most important inorganic phosphorus pools appear to be NAI-P and A-P (Golterman, 2004). Table 7 shows the amount and proportion of the different forms of phosphorus in the undisturbed sediments at each depth. It was observed that the dominant phosphorus existence types at near the inlet of the CW were NAI-P and R-P constituting to 59% and 32% of the TP, respectively. It suggests that most of the particles of the influent are made up of inorganic materials and dead cells. However, in the middle part at inlet of cell 3, R-P (58%) is greater than NAI-P (39%), which means that most of the sediments have dead cells. It is assumed that the soluble P was transferred to the microorganisms' body cells in the aeration basin at cell 2 and accumulated there.

2.6 Relationship between water quality and disturbed sediments

The chemical compounds of disturbed sediments were compared with water quality data, as shown in Fig. 3. The DO in cell 2 was highly increased due to aeration. The organics as well as nutrients were reduced in cell 3. It was assumed that most of the dead cells were transported from water to sediment which resulted an increase in the residual pollutant content, like in the case of TP (Table 7) wherein the percentage of R-P increased along the path of the CW.

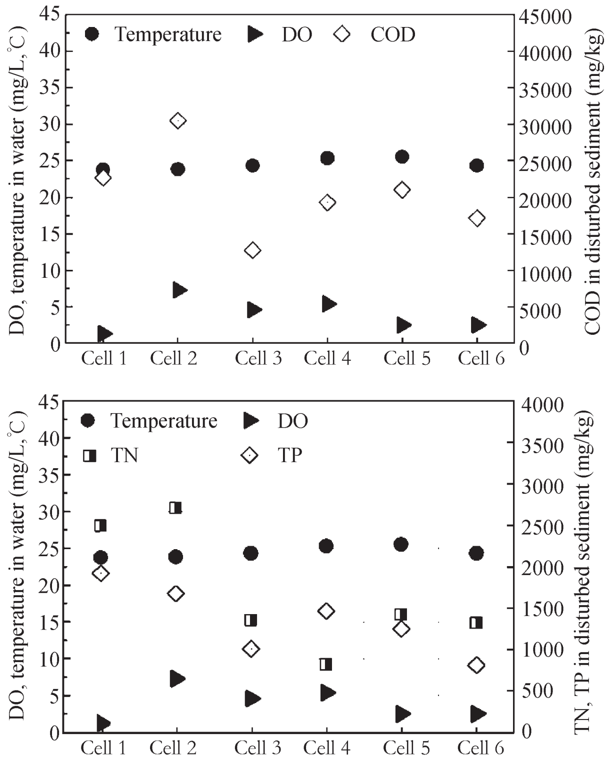

Fig. 3 Chemical compounds of water and disturbed sediment for each set of cells.

3 Conclusions

This investigation evaluated sediment characteristics including pollutant concentrations, phosphorus existence types, and water quality in a FWS CW. Based on the results, the concentrations of some water quality constituents were not significantly reduced because the influent concentration coming from the treated piggery wastewater contains appreciably high amounts of nitrogen and phosphorus and a low organic content. The mean pollutant concentrations of some water quality and disturbed sediments were highest at the influent of cell 4 from cell 5. The results reveal that the dominant phosphorus existence types at near the inlet of the CW were NAI-P (59%) and R-P (32%) suggesting that most of the particles of the influent are made up of inorganic materials and dead cells. Meanwhile, as the path in the CW progressed, the R-P in the accumulated sediment is increasing as the dead cells were transported from water to sediment. The findings on the phosphorus existence types in wetland sediments are important contribution on the knowledge of particles deposited in the CW and are useful in designing the CW; for instance, the location and length of the sedimentation basin. In addition, it can be helpful to determine the maintenance requirements of the CW and methods of reducing the phosphorus release from sediments. While the data are not sufficient enough to state the actual performance of the CW, continuous monitoring will be conducted in the future research.

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