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Nitrogen mass balance in a constructed wetland treating piggery wastewater effluent

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ABSTRACT

The nitrogen changes and the nitrogen mass balance in a free water surface flow constructed wetland (CW) using the four-year monitoring data from 2008 to 2012 were estimated. The CW was composed of six cells in series that include the first settling basin (Cell 1), aeration pond (Cell 2), deep marsh (Cell 3), shallow marsh (Cell 4), deep marsh (Cell 5) and final settling basin (Cell 6). Analysis revealed that the NH_4^+-N concentration decreased because of ammonification which was then followed by nitrification. The NO_3^--N and NO_2^--N were also further reduced by means of microbial activities and plant uptake during photosynthesis. The average nitrogen concentration at the influent was 37,819 kg/year and approximately 45% of that amount exited the CW in the effluent. The denitrification amounted to 34% of the net nitrogen input, whereas the accretion of sediment was only 7%. The biomass uptake of plants was able to retain only 1% of total nitrogen load. In order to improve the nutrient removal by plant uptake, plant coverage in four cells (i.e., Cells 1, 3, 4 and 5) could be increased.

Introduction

Constructed wetlands (CWs) are usually classified as an artificially restored aqua-ecosystem in Korea. Various measures were proposed by the Ministry of Environment (MOE) to reduce pollutant loadings from livestock wastewater with nonpoint source pollution. The processed livestock wastewater from wastewater treatment plants, excretions (e.g. nightsoil wastewater), sewage (e.g. municipal wastewater), liquid fertilizer and composted fertilizer present in land forms (e.g. dry and wet paddy fields), and many of un-disposed or untreated wastewaters were either returned to and used in agricultural lands or directly discharged to the rivers (MOA and MOE, 2004). These wastewaters still contain high levels of contaminants subsequent to treatment and therefore when introduced to agricultural lands or rivers might result to soil pollutant accumulation and groundwater contamination (Choi et al., 2001). Furthermore, when released to the ecosystem without proper disposal, it will certainly lead to river water quality deterioration and eutrophication, odor problems caused by the decomposition of organic matter, and abundance of insects and disease problems (Semmens et al., 1990). Eventually, the MOE has adapted to the use of CW or retention pond as post-treatment facilities to protect the water quality of its watersheds.

CWs have been applied to treat a variety of wastewaters including secondary wastewater treatment facility effluent, mine wastes, stormwater, and nonpoint source pollution (Moshiri, 1993; Tanner et al., 1995; Vymazal et al., 1998; Gottschall et al., 2007; Dong et al., 2012). The healthy wetlands can be obtained by providing balanced nutrients. Various types of CWs can be combined to

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achieve higher wastewater treatment effects, especially for nitrogen (Hammer, 1989). Nitrogen, a major component of municipal wastewater, stormwater runoff, and industrial wastewater, is potentially toxic to aquatic organisms and plays a role in eutrophication (Vymazal, 2007). Nitrogen removal in wetlands takes place mainly through the mechanisms of nitrification, denitrification, plant uptake and sedimentation (Vymazal et al., 1998). However, only few processes ultimately remove total nitrogen (TN) from the wastewater while most processes just convert nitrogen to its various forms. The most important inorganic forms of nitrogen in wetlands are ammonium (NH_4^+), nitrite (NO_2^-) and nitrate (NO_3^-) (Vymazal, 2007). The ammonium and nitrate uptaken by plants are stored in organic form in wetland vegetation. In addition to the physical translocation of nitrogen compounds in wetlands, the processes involved in nitrogen transformation are ammonification, nitrification, denitrification, nitrogen fixation, and nitrogen assimilation. Ammonification is the microbial conversion of organic nitrogen to ammonia. The energy released in this multistep, biochemical process is incorporated into the microbial biomass (Brix and Schierup, 1989; Vymazal, 2001, 2007).

This research focused on nitrogen changes and mass balance in a free water surface (FWS) flow CW. The main objectives were to estimate the nitrogen mass balance by comparing the nitrogen concentration in the influent, effluent, sediment and plants to assess the nitrogen removal efficiency of the CW. The specific objective was to investigate the nitrogen forms and concentration changes in each cell of the CW.

1 Materials and methods

1.1 Constructed wetland location and design

The FWS CW was constructed by the MOE in 2007 and located at 36°07′12″N and 127°08′15″E in Nonsan City, Chungcheong Province, Korea (**Fig. 1**). The CW was designed as the final stage of a wastewater treatment plants treating piggery wastewater produced by around 30,000 swine with an average rate of 135 m^3/day during dry days and stormwater runoff from an 11 ha livestock landuse area during wet days. The influent was contaminated with high organic matters and nutrients that finally discharge into the Geum River. The climate of the region is monsoon and temperate, and majority of rainfall occurs during the summer season from June until August. **Table 1** presents the design characteristics of the CW. The CW has a total

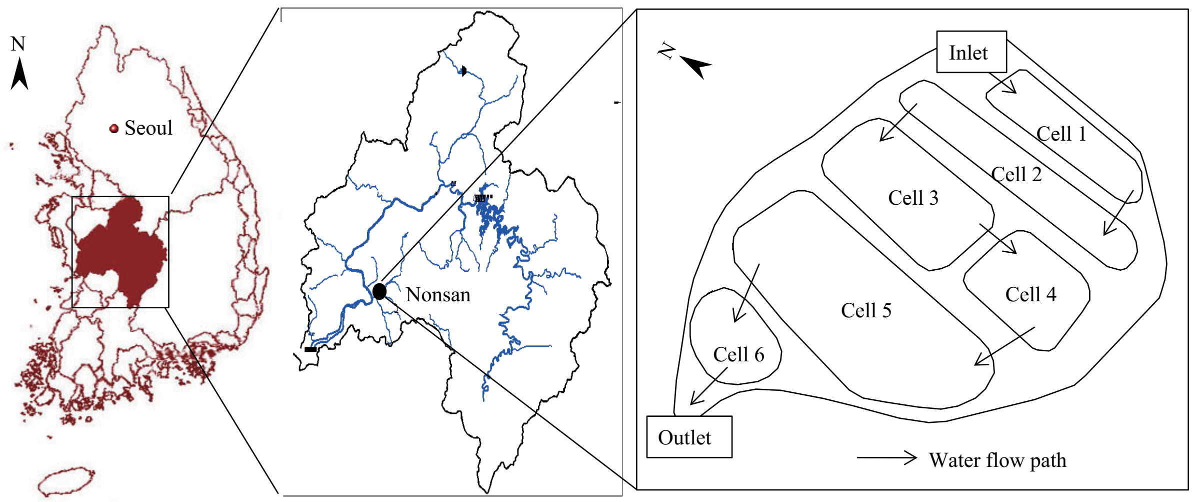

Fig. 1 Location of the constructed wetland (CW) in Nonsan City, Korea.

Table 1 Design characteristics of the CW

Design criteria	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Total
Function	Settling basin	Aeration pond	Deep marsh	Shallow marsh	Deep marsh	Settling basin	–
Surface area (m^2)	560	776	805	527	1474	350	4492
Storage volume (m^3)	453	565	810	280	1626	272	4006
Water depth (m)	0.8	0.7	1.0	0.5	1.1	0.8	–
HRT for design flow (hr)	5.5	6.8	9.8	3.4	19.6	3.3	48.4
HRT for peak flow (hr)	1.6	2.0	2.9	1.0	5.8	1.0	14.3
Dominant plant	PA	PA	PA	MS	PA		

HRT: hydraulic retention time; PA: *Phragmites australis*; MS: *Miscanthus sacchariflorus*.

storage volume of 4006 m^3 and hydraulic retention time of 48 hr from the inlet to outlet during dry days. The CW served to perform different treatment mechanisms such as sedimentation of particulates in Cell 1, enhanced biological treatment using aeration of coarse-bubble diffuser system in Cell 2, and enhanced sedimentation of organics in the subsequent regions of Cells 3 to 6. Oxygen supply in Cell 2 was operating during 3 hr and stopped during 3 hr. Two typical types of wetland plants such as *Phragmites australis* (PA) and *Miscanthus sacchariflorus* (MS) were planted surrounding the water zone of the CW. The initial average vegetation density varied between 6.7 kg/m^2 in spring and 0.9 kg/m^2 in winter.

1.2 Water quality, sediment and plant monitoring

The monitoring was performed during dry days on a minimum of three days after a storm from October 2008 to December 2012. The water quality samples were collected at seven sampling locations (i.e., the inlets of Cells 1 to 6 and the outlet) and analyzed for dissolved oxygen (DO), pH, temperature, TN, total Kjeldahl nitrogen (TKN), NH_4^+-N, NO_3^--N and NO_2^--N. All analytical analyses performed were based on the standard methods for the examination of water and wastewater (APHA et al., 2005). Undisturbed sediment samples were manually collected to measure nitrogen content (Carter and Gregorich, 2006) and depth of the accumulated soil and sediment using an acryl tube, 5 cm in diameter and 50 cm long. Plant monitoring was carried out during the macrophytes life cycle since April 2009. A total of 15 biomass samples including shoot of plant were collected within a 30 × 30 cm quadrant from Cells 1 to 5. The collected plants were oven dried at 80°C and the water content of the plant biomass was determined.

1.3 Data analyses and calculation of chemical compositions

Results were statistically analyzed using SYSTAT 9.0 (©Systat Software, Inc., Chicago, IL, USA, 2007) and OriginPro 8 SRO v8.0724 (B724) (©OriginLab Corporation, Northampton, MA, USA, 1991–2007) software package including analysis of variance (one-way ANOVA). The differences were accepted as significant at the $p = 0.05$ level. The nitrogen content in plant was measured using Kjeldahl method and calculated as the amount of N (mg) per dry weight (g) of N. The nitrogen mass balance in the CW can be expressed using Eq. (1):

$$N_{in} = N_{out} + N_s + N_p + N_g + N_r \quad (1)$$

where, N_{in} (mg/g) represents the amount of nitrogen from influent, N_{out} (mg/g) represents the effluent; N_s (mg/g) represent the nitrogen accumulated into the soil and sediment, N_p (mg/g) represents the nitrogen assimilated into plants; N_g (mg/g) represents the nitrogen that was lost through gasification and N_r (mg/g) represents the amount of nitrogen retention rate in the CW.

2 Results and discussion

2.1 Temperatures, DO and pH in water

Figure 2 shows the monthly water temperature, DO and pH of influent and effluent in the CW during the monitoring period. The average values of influent and effluent temperatures were (18.2 ± 6.9)°C and (16.9 ± 8.1)°C, respectively. The monthly temperatures in the influent and effluent of the CW were not significantly different. The highest temperatures (influent: 27.3°C, effluent: 28.2°C) were reached in July, and the lowest temperatures (influent: 8.2°C, effluent: 5.3°C) were recorded in January. The wetland water temperature could influence the biological treatment processes. Warmer temperatures decrease oxygen solubility in water increasing metabolic rates that affect nitrification, sediment oxygen demand and photosynthesis (Kadlec, 1999; Gorme et al., 2012). The highest (6.0 mg/L) and lowest DO (1.8 mg/L) concentrations of influent occurred in winter and summer season, respectively. The DO concentration increased between influent (3.6 ± 1.3 mg/L) and effluent (4.3 ± 1.0 mg/L). The DO concentration was increased from April to May due to algal blooming at the deep marsh 2 (Cell 5). Algae can drive the pH of wetland waters to high values during periods of high productivity, especially in open water zones within wetlands (Gorme et al., 2012). Therefore, the highest pH occurred in April with 10.5 for influent and 11.1 for effluent. The monthly temperature, DO and pH in the CW showed no significant change between the influent and effluent ($p > 0.05$).

2.2 Nitrogen changes and removal efficiency in the CW

Figure 3 illustrates the changes of nitrogen concentration along the cells from influent to effluent during dry days. All nitrogen forms were significantly reduced ($p < 0.05$) with respect to influent concentration except NO_2^--N and organic-N ($p > 0.05$). Particulate nitrogen was trapped in settling zone and converted into its soluble forms. The

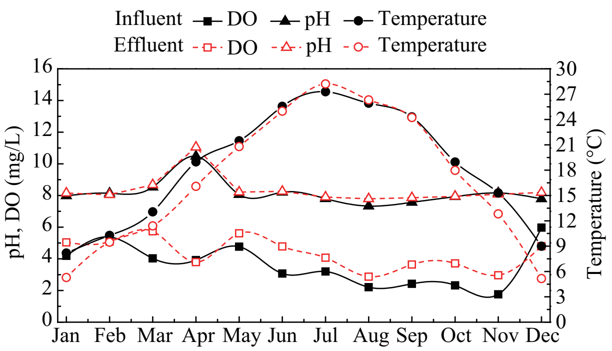

Fig. 2 Average monthly temperature, DO and pH at the influent and effluent during the monitoring period between October 2008 and December 2012.

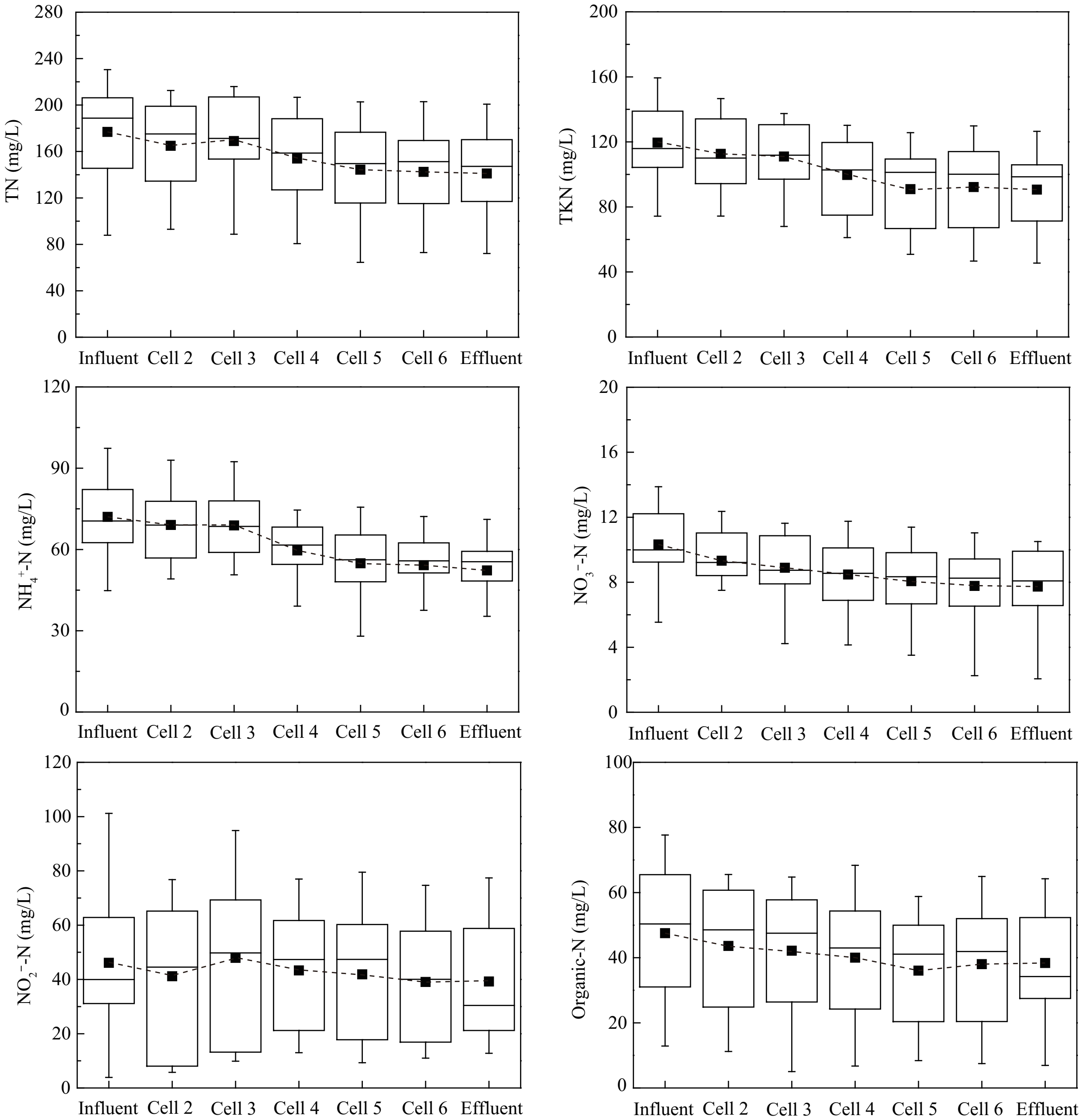

Fig. 3 Nitrogen concentration changes in each cell during dry days.

results showed that the average concentrations of nitrogen forms decreased after passing Cell 1 (settling basin) and TN, TKN, NO_2^--N and organic-N were increased at Cell 3 (deep march) due to oxygen supply in Cell 2 (aeration pond). The occurrence of both aeration and low oxygen conditions suggests that the nitrification and denitrification processes would occur simultaneously in Cell 2 which resulted to the decrease of both NH_4^+-N and NO_3^--N. Moreover, high NO_2^--N measurements were observed in Cell 3 suggesting that the intermediate products of nitrification and denitrification were accumulated in the CW. Nitrification coupled with denitrification seems to be the major removal process in the CW. Denitrification is considered as a major removal mechanism for nitrogen in most types of CWs (Vymazal, 2007). The process of ammonification as such does not remove nitrogen from the wastewater in the CW. It just converts organic nitrogen to ammonia which is then available for other processes (e.g., nitrification, volatilization, adsorption, plant uptake) (Vymazal, 2007; Zhang et al., 2009). On the other hand, NO_3^--N concentration was very low compared to other nitrogen forms. Generally, the concentrations of nitrate are very low in wastewater (the exception is drainage water from the agriculture and some industrial wastewaters) (Vymazal, 2007).

Figure 4 shows the average forms of nitrogen for the influent and effluent in the CW. Nutrient speciation of FWS CWs in other publications also varies from this

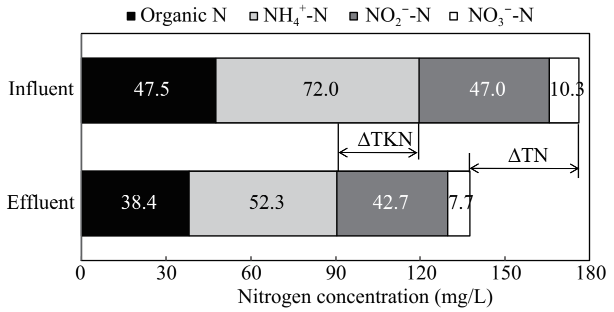

Fig. 4 Average nitrogen forms for influent and effluent in the CW.

study depending on wastewater type (Cameron et al., 2003; Mercado et al., 2013). As can be seen, the influent NH_4^+-N constituted to about 41% (72.0 mg/L) of TN while NO_3^--N was only 6% (10.3 mg/L), while the effluent forms showed 37% (52.3 mg/L) for NH_4^+-N and 6% (7.7 mg/L) for NO_3^--N. Compared to the other forms of nitrogen, NH_4^+-N fraction of TN was high due to high NH_4^+-N concentration in livestock wastewater especially treating piggery wastewater. The various forms of nitrogen are continually involved in chemical transformations from inorganic to organic compounds and back from organic to inorganic (Vymazal, 2007). NH_4^+-N achieved the highest removal efficiency of 27% while TN showed the lowest removal efficiency of 20%. The reduction of NH_4^+-N was attributed to plant uptake and its sorption to detritus and inorganic sediment since NH_4^+-N bound loosely to the substrate and easily released when water environment conditions change (Kovacic et al., 2006).

2.3 Nitrogen content in sediment

The TN content in undisturbed sediment at each sampling location is shown in **Fig. 5**. The result showed that the average TN content from Cell 1 to Cell 3 decreased from (638.5 ± 374.3) to (368.6 ± 311.4) mg/(kg·month). The TN content was highest at the inlet of Cell 1 compared to other samples signifying that lots of particulates were precipitated in the cell by sedimentation and intercepted by plant. The amount of nutrients in accumulated sediment is relatively pre-treatment system such as first settling basin because the main mechanism of pollutant removal in the CW is sedimentation. A research by El-Sheikh et al. (2010) showed that the particulate matters increased in the first treatment bed followed by a decrease with distance along the bed.

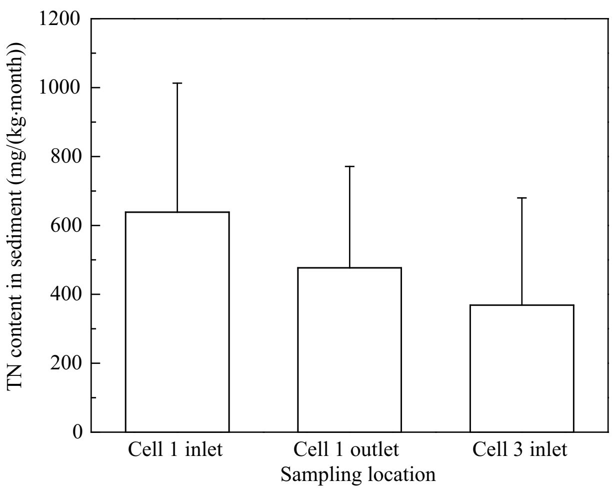

Fig. 5 TN contents in sediment of the CW. Data are presented as mean ± S.D.

2.4 Nitrogen content in plants

Figure 6 shows the monthly nitrogen content of the different plants at each cell of the CW measured between May and December in 2011. During the monitoring period between 2009 and 2010, it was observed that the density of MS planted in Cell 4 decreased in the water zone and grew only outside the boundary of the water zone. Thus, only the average nitrogen content of the PA plants was provided in **Fig. 6**. The highest nitrogen content of PA occurred in September with 958.6 g/m^2 at Cell 3. One of the reasons for the high nitrogen content is that the influent contains an appreciably high amount of nutrient from piggery wastewater effluent and contaminated stormwater since summer season. High levels of nutrients entering the CW system denote high plant biomass rate because many of the nutrients are assimilated and stored in the plant system (Engloner, 2009; Lee et al., 2013). The average nitrogen content in Cell 1 and 3 corresponded to the lowest values (134 ± 86 g/m^2) and highest values (372 ± 310 g/m^2), respectively. The proportion of biomass coverage to surface area in Cell 3 was the highest among treatment regions during the plant biomass lifecycle, which led to high nutrient content in plant.

2.5 Nitrogen mass balance in the CW

Figure 7 shows the nitrogen mass balance in the CW during the monitoring period. Average nitrogen concentration at the influent was estimated to be 37,819 kg/year wherein 45% (17,067 kg/year) of this input nitrogen exited in the effluent of the CW. The plant uptake by two dominant plant species was 262 kg/year or 1% of the nitrogen input. The main reason for the low plant uptake rate was that the average proportion of biomass coverage to total coverage

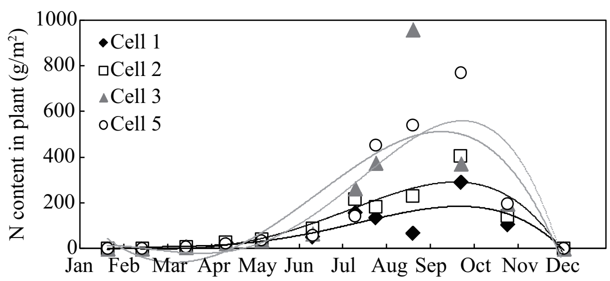

Fig. 6 Monthly nitrogen content of different plants.

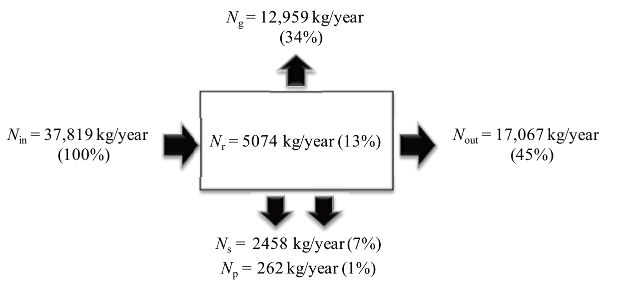

Fig. 7 Nitrogen mass balance in the CW. N_{in} (mg/g): nitrogen from influent, N_{out} (mg/g) nitrogen in effluent; N_s (mg/g): nitrogen accumulated into the soil and sediment, N_p: nitrogen assimilated into plants; N_g: nitrogen lost through gasification, N_r (mg/g): nitrogen retention rate.

area of CW was small that was only less than 3% during the plant biomass lifecycle. The accumulation of nutrients depends on the concentrations of both elements in the plant tissue as well as on the amount of plant biomass (Vymazal, 2004). Denitrification was amounted to 34% of the net nitrogen input, whereas accretion of sediment represents only 7%. The mass balance calculation was a practical method of predicting the amount of nitrogen in the CW. This knowledge is particularly useful for the management and operation of CW.

3 Conclusions

This research focused on the evaluation of the nitrogen changes and the estimation of the nitrogen mass balance in the FWS CW by comparing the nitrogen concentrations in the influent, effluent, sediment and plants using a four-year monitoring data. Findings revealed that NH_4^+-N achieved the highest removal efficiency of 27% while TN showed the lowest removal efficiency of 20%. The NH_4^+-N fraction of TN was high compared to other forms of nitrogen due to the high NH_4^+-N concentration in livestock wastewater especially treating piggery wastewater. The occurrence of both aeration and low oxygen conditions suggested that the nitrification and denitrification processes could occur simultaneously in Cell 2 which resulted to the decrease of both NH_4^+-N and NO_3^--N. Moreover, high NO_2^--N measurements were observed in Cell 2 denoting that the intermediate products of nitrification and denitrification were accumulated in the CW. The TN content in sediment showed that the average TN from Cell 1 to Cell 3 decreased, signifying that many particulates were precipitated in the cells by sedimentation. The average nitrogen content of plants in the Cells obtained ranged from (134 ± 86) to (372 ± 310) g/m^2. Based on the nitrogen mass balance, denitrification was amounted to 34% of the net nitrogen input, whereas accretion of sediment represents only 7%. The plant uptake was only about 1% of nitrogen. In order to increase the nutrient removal rate by plant uptake, four basins including the first settling basin (Cell 1), deep and shallow marshes (Cells 3 to 5) was suggested to be covered by plants. The findings on the mass circulation in the CW system provided important information regarding the pollutant fate because it is concerned with pollutant reduction in the field of environmental engineering. The estimated nitrogen mass balance was effective in predicting the nitrogen retention and release in the CW needed to treat wastewater.

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