Desalination and Water Treatment
www.deswater.com

1944-3994/1944-3986
doi: 10/5004/dwt.2012.3223

Taylor & Francis
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45 (2012) 136–143
July

Seasonal changes of plant biomass at a constructed wetland in a livestock watershed area

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Received 25 August 2011; Accepted 2 November 2011

ABSTRACT

Monitoring was conducted to evaluate the seasonal changes in plant biomass in a free water surface constructed wetland (CW) located in Nonsan City, South Korea. Korea has temperate climate so plant growth is in the summer and senescence during the winter. Plant biomass measurements were taken during the plant life cycle from May to October 2009. Two dominant plant species, *Phragmites australis and Miscanthus sacchariflorus*, were analyzed for the measurement of the weight, height, count and total planted area. To assess the health of plants, the relative growth rate (RGR) was also calculated. The increase in plant productivity is attributed to the increase in the availability of water, light, temperature and nutrients. Results showed that high plant biomass rate was observed during the summer season. The growth of plants stopped during autumn while a gradual decrease of plant count was observed during the end of summer. Since summer season is a period of most nutrient loadings coming from the livestock wastewater treatment plant and stormwater runoff, high levels of nutrients subjected into a CW system thereby increasing plant biomass rate because many of the nutrients are assimilated and stored into the plant system. However, the RGR of plants decrease as plants age.

Keywords: Constructed wetland; Nutrients; Plant biomass; Relative growth rate; Temperature

1. Introduction

The use of constructed wetlands (CWs) is fast becoming a common alternative and widely accepted method for the treatment of wastewater. Initially, CWs were mainly used for nutrient retention from stormwater and agricultural runoff [1]. In Korea, various measures were proposed by the Ministry of Environment (MOE) to reduce pollutant loadings from livestock wastewater. Eventually, the MOE has adapted to the use of CW to protect the water quality of its watersheds. Since CWs have high rate of biological activity, they can transform many of the common pollutants that occur in conventional wastewater, such as livestock wastewater, into harmless byproducts of essential nutrients that can be used for additional biological productivity [2,3].

Several studies were conducted assessing the applicability of CW to treat livestock wastewater. Meers et al. [4] effectively applied CW technology in transforming liquid fraction of pig manure into re-usable/dischargeable water with sufficient quality regarding N, P and COD content [4]. This could be achieved through various processes including filtration, sedimentation, bacterial transformation and assimilation through aquatic vegetation. The extent of

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wastewater treatment system depends upon the wetland design, inflow concentration, mass loading rates, microbial community, and types of plants involved [5]. The benefits of plants in CW were studied by [1,6].

The function of plants in CW is largely to grow and die. Plant growth provides a vegetative mass that deflects flows, allows transpiration, particulate trapping, and uptake and cycling of nutrients. They not only assimilate pollutants directly into their tissues, but also act as catalyst for purification reactions [6]. The presence of vegetation in CW influences the supply of oxygen to the water and provides substrate for microbes and epiphytes, which process pollutants [7]. Death of plants creates litter and releases carbon which supplies the energy needed for heterotrophic denitrifiers.

Macrophyte productivity varies with seasonal changes in temperature within natural environments [8]. Korea has temperate climate, so plant growth is limited to the growing season. A distinct seasonal response in vegetation phenology is noted in temperate wetland systems, where there is growth in the summer and senescence in the winter. Typically, months and years are required for the vegetative compartments to fully develop [7]. Most of wetland plants in FWS CW are perennial plants. Perennial plants distinguish themselves from other plants in their ability to suspend and resume growth recurrently in response to the environmental and seasonal conditions. For temperate climate, it flowers and sets seed each spring or summer, goes dormant each winter while storing energy in its roots, and grows back in spring of the next growing season.

The influence of the lifecycle of plants in the processing of nutrients is an important factor in evaluating the applicability of CW in treating livestock wastewater. The objective of this study was to investigate the seasonal changes of plant biomass in the CW during its first growing year. The factors that affect plant growth and the season where plant biomass growth is at its highest were determined. The growth rate of the plants was calculated to assess the growth pattern of the plants.

2. Materials and methods

2.1. Site description

The site of the free water surface CW is located in Nonsan City, South Chungcheong Province, Korea. The climate of the region is temperate with air temperatures ranging from 10°C to 30°C during spring and summer, and between −7°C and 11°C during fall and winter. It was built by the MOE in 2007 and operation started in September 2008. The 110,000 m^2 catchment area of this facility are mostly paved and has an urban type of land use. Influent flowing through the CW came for the livestock wastewater treatment plant during dry days with an addition of stormwater runoff during wet days. Influents in CW are contaminated with organic matters, nutrients and pollutants coming from livestock waste and non-point sources.

2.2. Constructed wetland configuration

The CW is composed of six cells performing different treatment mechanisms. The CW has a total surface area of 4492 m^2 and a total storage volume of 4006 m^3. Table 1 summarizes the specific components and dimensions of the CW. Influents are initially treated in the settling basin where sedimentation of particulates occurs. It is followed by aeration in the second cell, and further sedimentation and treatment by vegetation occurs in the subsequent cells. The hydraulic retention time (HRT) of treating wastewater from the inlet to outlet is approximately 48 h. Wetland plants are considered to be the main biological component in the CW. Plants were selected based on their ability to grow fast, capacity to remove contaminants and high toxicity tolerance. Table 2 provides the detailed information of the plant species in

Table 1
Specification of the constructed wetland

Cell no.	Description	Surface area (m^2)	Storage volume (m^3)	Water depth (cm)	HRT for design flow (h)	HRT forpeak flow (h)
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

Table 2
Dominant plant species planted in the constructed wetland

Scientific name	Common name	No. of plants	Cultivated cell
Phragmites australis	Common reed	23,400	Cells 1, 2, 3 and 5
Typha angustata	Indian reed mace	2800	Cells 3 and 5
Miscanthus sacchariflorus	Silver banner grass	800	Cell 4
Phragmites japonica	Reed	4100	Cell 4
Nelumbo nucifera	Lotus	1800	Cell 6

the CW. Majority of the cells in the CW are inhabited with *Phragmites australis*.

2.3. Water quality monitoring

Monitoring was conducted during dry seasons from October 2008 to October 2009. Shown in Fig. 1 are the six sampling points collected at inlets from Cells 1 to 5 and at the outlet to determine the pollutant concentration in each cell. A 24 h monitoring was also conducted wherein samples were collected at the inlet and outlet every 3 h in one day to assess the operation of the CW. Parameters such as temperature, pH, conductivity, dissolved oxygen (DO), turbidity were measured on site using portable meters and then samples were transported to the laboratory to analyze the total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved organic carbon (DOC), total nitrogen (TN), total Kjeldahl nitrogen (TKN), nitrate (NO_3-N), ammonium (NH_4-N), total phosphorus (TP) and orthophosphate (PO_4-P) concentration in the samples. Analyses were performed in accordance to standard methods for examination of wastewater. Rainfall and air temperature data were taken from the Korea Meteorological Administration.

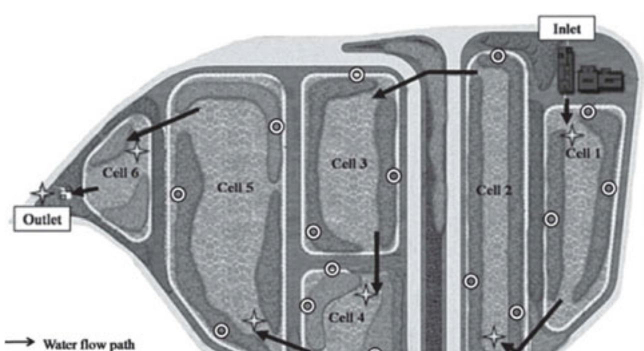

Fig. 1. Plan view of the site with water and plant biomass sampling points.

2.4. Plant biomass monitoring

Plant biomass measurements were carried out during the macrophytes life cycle between May to October 2009. Plants were sampled within 30 × 30 cm quadrant that is proximal to the inlet and outlet of the CW to measure the weight of plant biomass per unit area. Two of the six plant species (Fig. 2) were selected for monitoring, *Phragmites australis* and *Miscanthus sacchariflorus*. A total of 15 plant biomass samples were collected from Cells 1 to 5. The plant count and average plant height for each quadrant were measured and a sample plant representation was cut at the ground level. The collected plants were dried in the oven until constant weight was achieved. The relative growth rate of plants (RGR) was calculated according to the equation proposed by Hunt [9]:

$$RGR = (\ln W_2 - \ln W_1)/(T_2 - T_1)$$

where W_1 and W_2 are the initial and final dry weight in grams; T_1 and T_2 are the beginning and end of sampling period in days.

3. Results and discussions

3.1. Water quality

Table 3 summarizes the variables measured in the influent and effluent of the wetland and the estimated

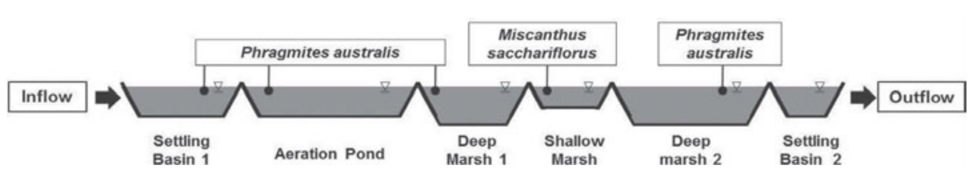

Fig. 2. Schematic representation of the CW system with the dominant plant species.

Table 3
Influent, effluent and mean removal percentages in the constructed wetland

Parameter (unit)	Influent		Effluent		% Removal
	Mean	Range	Mean	Range	
pH (pH unit)	7.9	6.4–8.8	8.1	7.2–8.9	–
Conductivity (μs cm^{-1})	5269.2	1207–12,180	5525.6	1138–12180	–
BOD (mg l^{-1})	63.7	16.05–131.08	41	13.3–81.3	36
TSS (mg l^{-1})	60.1	24–104	29	10–48	52
DO (mg l^{-1})	3.7	0.64–10.3	6.4	0.65–12.9	–
TN (mg l^{-1})	137.0	84.3–230.5	120.6	72.7–191.4	12
TP (mg l^{-1})	5.2	1.882–9.482	3.6	0.995–7.8	31
NH_4-N (mg l^{-1})	39.2	11.5–73.9	31.9	9.5–68.3	19
TKN (mg l^{-1})	78.1	52.4–117.3	65.9	40.7–104.3	16
NO_3 (mg l^{-1})	10.2	3.1–14.6	8.2	1.3–12.5	19
COD_{mn} (mg l^{-1})	130.4	36–232	95.9	28–166	26
PO_4-P (mg l^{-1})	1.5	0.15–4.7	0.99	0.1–2.7	33
DOC (mg l^{-1})	79.6	24.4–136.6	57.7	16.4–97.6	27

removal efficiencies. The mean removal efficiencies were calculated from the relevant inlet and outlet pollutant loadings that have been analyzed statistically for 20 dry monitoring sampling events. The magnitude of reductions depends on several factors including inflow concentrations, chemical form of the nutrients, water temperature, season, and DO [2]. Of all the parameters, TSS achieved the highest removal efficiency of 52%. There is an effective particulate removal of suspended solids and particulates since settleable incoming particulate matter usually has ample time to settle and become trapped in litter and dead zones of the plants due to the subsequent low velocity and laminar flow in the CW. Once they are trapped, soluble organic constituents are reduced to carbon dioxide and become buried through sediment accretion [7]. Meanwhile, nitrogen forms obtained relatively low removal efficiency, having TN as the lowest with 12%. Gersberg et al. [10] reported that TN removal via plant uptake accounts for a small fraction of the overall nitrogen removal as denitrification through anaerobic respiration remains the most effective procedure for nitrogen removal in heavily nitrified secondary wastewaters [10]. Most of the influent pollutant concentration has decreased. However, the mean concentration removal efficiencies were still below 50%. It was observed that the average organic content (BOD, COD and DOC) of the livestock wastewater was low compared to TN. In the case when nutrients are extremely high, there would not be enough organics to biologically treat the wastewater. This resulted to low treatment efficiencies of BOD, COD and DOC of 36%, 26% and 27%, respectively. In the case of phosphorus forms such as TP and PO_4-P, the average removal efficiencies were 31% and 33%, respectively. Phosphorus forms in wastewater can be effectively removed from water through sedimentation and plant uptake. However, since plants from this free water surface flow CW were located only at the sides of each cell, it was not sufficient to completely remove phosphorus from the water resulting to a low removal efficiency of phosphorus in water.

The temperature of wetland waters influences both the physical and biological processes within a CW. Fig. 3 shows the monthly air and water temperatures in the CW in 2009. The average values of influent and effluent temperatures are 17.8°C and 17.5°C, respectively while the average air temperature was 14.4°C. In particular, the respective correlations with atmospheric temperature

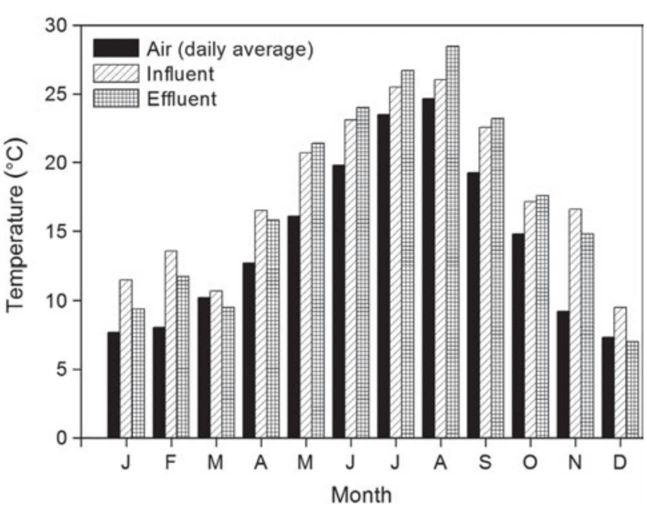

Fig. 3. Monthly air and water temperatures in 2009.

were 0.906 and 0.942 for the influent and effluent, respectively. The highest temperatures (air = 24.7°C, influent = 26.1°C, effluent = 28.5°C) were reached in August, and the lowest temperatures (air = 7.3°C, influent = 9.5°C, effluent = 7.0°C) were recorded in December. It was observed that the water temperature was warmer than air temperature. Since water is a transparent medium, it allows light to penetrate to depth thus, absorbing heat. Warmer temperatures decrease oxygen solubility in water increasing metabolic rates that affect nitrification, sediment oxygen demand and photosynthesis.

DO and pH concentration showed large variations all throughout the year as shown in Fig. 4. The highest DO (12.9 mg l^{-1}) occurred in July due to vast algal growth which resulted from excessive amount of nutrients from livestock waste and stormwater runoff. Algae can drive the pH of wetland waters to high values during periods of high productivity, especially in open water zones within wetlands. However, there was a sudden decrease of DO after July. High concentrations of nutrients introduced into the CW system increased the growth of algae and plants. However, growth of algae as well as its decay also increased rapidly which resulted to a high concentration of dead organic matter in the wetland water. The decomposition of organic matter by aerobic microorganisms and high water temperatures consumed a lot of DO in the water, resulting in hypoxic conditions.

3.2. Plant biomass growth

In a free water surface flow CW, water flows over a vegetated soil surface from inlet to outlet. Vegetation cover started to expand from May 2009. Plant biomass coverage in the CW was 227.3 m^2 in May, 434.4 m^2 in June and 535 m^2 in July. Fig. 5 shows the monthly plant biomass changes of *Phragmites australis* and *Miscanthus sacchariflorus* during its first growing season. The highest plant biomass rate of PA and MS both occurred in September with 8.09 and 6.9 kg m^{-2}, respectively. Photosynthesis cycle and nutrient uptake plays a major role in the growth of plants in the CW. Since both *Phragmites australis* and *Miscanthus sacchariflorus* are perennial plants, they grow during spring, become dormant during winter, and grow back during spring of the next growing season. *Phragmites australis* reached its maximum growth in summer months of July, August and September. There was a steady increase of plant biomass recorded from May to August which is similar to the results of Karunaratne et al. [11] wherein root plant biomass is relatively stable throughout the growing season [11]. The increase of plant productivity is mainly due to the increase in availability of water, light and nutrients.

According to Engloner [12], the high mean temperatures in spring and summer generally led to higher and earlier increases of plant biomass in the CW [12]. Since summer is the season where most rainfall occurs, many nutrients are being transported back into the CW that is added with the already heavily polluted livestock wastewater. Examples of studies on *Phragmites australis* are provided in Table 4.

The average plant biomass rate for this study was comparable to the results of Mueleman et al. [13] which treats wastewater nutrients at primary levels [13]. Difference in influent concentration causes variation in the plant biomass rate. Like for instance, high levels of nutrients subjected into a CW system denotes high plant biomass rate because many of the nutrients were assimilated and stored into the plant system. Fig. 6 shows that

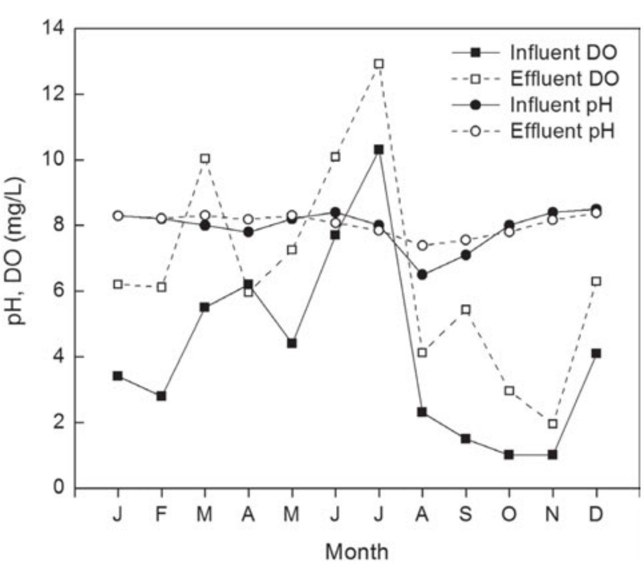

Fig. 4. Monthly influent and effluent pH and DO in the constructed in 2009.

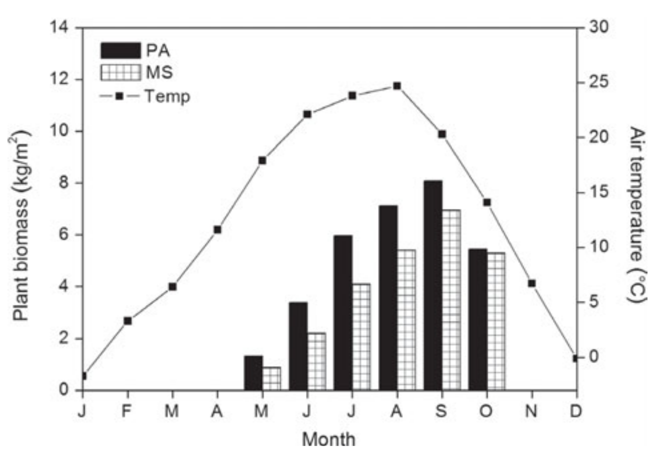

Fig. 5. Growth of biomass *Phragmites australis* (PA) and *Miscanthus sacchariflorus* (MS) in 2009.

Table 4
Biomass of *Phragmites australis* from other studies

Reference	Location	Type	Biomass (kg m^{-2})
Mueleman et al. [13]	The Netherlands	Nutrients at primary treatment levels	5.50
Greenway [14]	Brisbane	Nutrients at secondary treatment levels	2.52
Obarska-Pempkowiak and Ozimek [15]	Poland	Stormwater runoff	2.35
Barbera et al. [1]	Italy	Conventional wastewater treatment plant	4.7
This study	South Korea	Secondary piggery wastewater	5.2

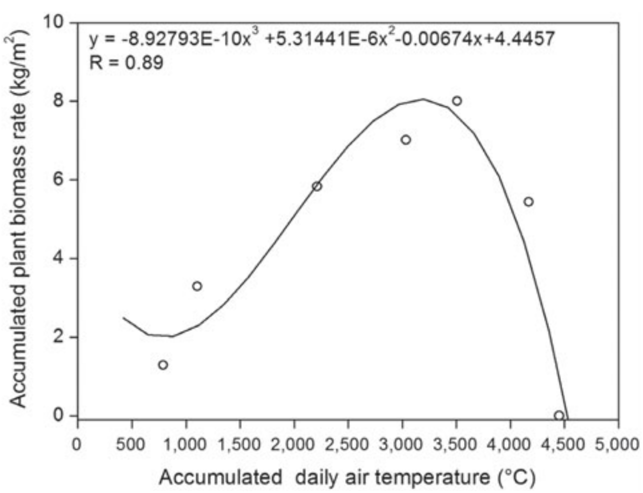

Fig. 6. Accumulated biomass vs. daily air temperature.

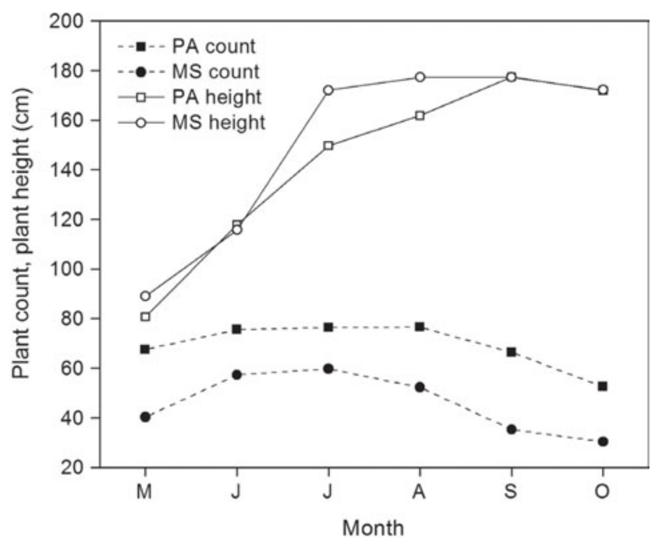

Fig. 7. Monthly biomass height and plant count of *Phragmites australis* (PA) and *Miscanthus sacchariflorus* (MS).

the maximum accumulated plant biomass was attained at accumulated daily air temperature of 3300°C. Plant biomass rate declined gradually as plant reaches the optimum temperature.

During the vegetation period, the average height curves of growing shoots are of sigmoid shape flattening from late June to August [12]. The plant count per unit area and the average height were measured during the monitoring period as shown in Fig. 7. The number of plant count for *Phragmites australis* was highest during August while plant count for *Miscanthus sacchariflorus* was utmost in September. Plant count ranges from 53 to 77 and 30 to 60 for *Phragmites australis* and *Miscanthus sacchariflorus*, respectively. All plant species showed consistent growth in terms of height and density. The height (177 cm) of both plants peaked during September. Zemlin et al. [16] reported that temperature has a strong influence on shoot growth during the main vegetation, but it has only a weak influence on the variation of morphological variables (height and diameter) by the end of the growing season [16]. According to Bastlova et al. [17], the number of shoots per plants, that of nodes and living leaves of shoots correlate positively with nutrient supply [17]. High nutrient availability brings about an increasing number, height, weight and diameter of shoots [12].

3.3. Relative growth rate

Apart from physical appearance, the RGR were evaluated to assess the health of the plants. Both *Phragmites australis* and *Miscanthus sacchariflorus* have similar trend for the RGR. The highest growth rate of *Phragmites australis* and *Miscanthus sacchariflorus* (Fig. 8) were 59 mg g^{-1} d and 58 mg g^{-1} d, respectively. It was observed that the fastest growth of plants occurred at the beginning of the vegetation period followed by gradual decrease of RGR 3 wk subsequent to the monitoring. The RGR of reed such as *Phragmites australis* and *Miscanthus sacchariflorus* were highest in April to May and growth was faster in

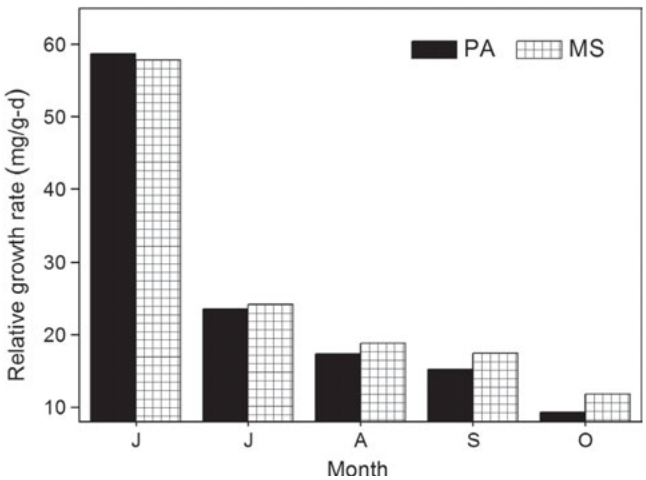

Fig. 8. Relative growth rate (RGR) of *Phragmites australis* (PA) and *Miscanthus sacchariflorus* (MS).

potentially taller than shorter shoots [12]. Consistently, the RGR of plants decreases with the age of plants [18]. It was known that the growth curve of plants has four stages which include lag phase, log/exponential phase, diminishing growth phase, and stationary phase. Based on this study, the lag phase occurred in May wherein the beginning of growth season and rate of plant growth was slow. The rate of growth then increased rapidly during the exponential phase which happened in June. After some time, the diminishing growth phase followed as the growth slowly decreased in June to October due to limitation of nutrients. The diminishing growth phase continued until it reached the stationary phase in which plant weight becomes constant which was observed in late October.

4. Conclusions

This study analyzed the seasonal biomass changes in the CW treating effluent from livestock wastewater treatment plant. Results showed that wetland species *Phragmites australis* and *Miscanthus sacchariflorus* obtained their highest biomass in September with 8.09 and 6.9 kg m^{-2}, respectively. Growth of plants stopped during autumn while a gradual decrease of plant count was observed during the end of summer. Increase in plant productivity was due to the increase in availability of water, light and nutrients. High levels of nutrients subjected into a CW system denoted high plant biomass rate since many of the nutrients were assimilated and stored into the plant system. The highest plant biomass occurred during the summer season from July to September as more nutrients were added to the CW due to surface runoff from heavy rainfall, aside from the high nutrient load discharges by the wastewater treatment plant. The trend of the plant growth rate showed that fast growth occurred at the beginning of the vegetation while a gradual decrease of growth was observed as plants mature.

Plants play a vital role in the filtration effect, residence for microbes and assimilation and uptake of nutrients from wastewater. However, a large portion of nutrients stored in plants may be later released and recycled as plants die and decompose. Therefore, lifecycle of plants contributes to the cycling of nutrients (absorption and leaching of nutrients) in the CW that significantly affects the overall treatment performance of the CW. Meanwhile, further studies and continuous monitoring will be conducted to evaluate the factors affecting plant productivity and wetland efficiency as a result of biomass aging and organic matter accumulation to optimize improvements in water quality.

Acknowledgements

The funding for this research was provided by the Construction Technology Renovation Research Project (10CCTI-C056937-01) from the Korea Ministry of Land, Transportation and Maritime Affairs. The authors are grateful for their support.

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