Comparison Study of Pulsing and Continuous Flow for Improving Effluent Water Quality and Plant Growth of a Constructed Wetland to Treat Domestic Wastewater

S. Sasikala, N. Tanaka[1], K.B.S. N. Jinadasa[2] and M.I.M. Mowjood[3]

Department of Agricultural Engineering
Faculty of Agriculture
University of Peradeniya, Sri Lanka

ABSTRACT. *A wetland used for wastewater treatment should be incorporated with oxygen. One method to improve oxygen concentration in wetland is flow modification. In this study the effect of pulsed sewage water feed on treatment efficiency of free-surface-flow constructed wetlands was studied. This research was conducted in two phases from January to June and June to September in 2006. Two wetland units (L1 and L2) were planted with Scirpus grossus; L1 received a continuous wastewater feed (CF) and L2 a pulsed feed (PF; five days of feed followed by two days of no feed). The removal of biological oxygen demand (BOD_5), ammonium nitrogen (NH_4-N), and nitrate nitrogen (NO_3-N) were analysed for effluent, and total Kjeldahl nitrogen (TKN) and total phosphorous (TP) in the substrate of both units were compared. Plant growth was monitored continuously for both systems. BOD_5 removal was increased by 14% by the pulsing application compared to the CF application. The average removal rate of NO_3-N was 36% and 45% in CF and PF respectively and the differences were statistically significant. The average removal of NH_4-N was 27.5% and 24.0% in CF and PF, which were not significantly different. The TKN near the outlet was ~5 mg per 100 g soil in both units. However, TP was higher (~22 mg per 100 g soil) at the outlet of the PF unit compared to the CF unit (~12 mg per 100 g soil). The maximum plant height was 220 cm in both systems, and no significant difference was observed. In contrast, the PF unit showed a significant reduction in shoot density and biomass production of S. grossus compared to the CF unit. The results of this study indicate that the pulse feeding strategy improved the removal of BOD_5 and reduced the above ground biomass production compared to the continuous feeding system. However, no clear improvement in ammonium removal was observed in the PF system in comparison to previous studies.*

INTRODUCTION

The potential of Constructed Wetlands (CWs) as a secondary treatment for domestic wastewater was found to be significant (Headley *et al*., 2005). Human waste can have a significant level of ammonium nitrogen (NH_4-N) and organic N (Huang *et al*., 2000). Unsuitable conditions for the removal of ammonium nitrogen can seriously limit the treatment performance of a wetland system (Clarke *et al.*, 2002). The biochemical processes require the establishment of oxygen-enriched zones (Garcia *et al*., 2005; Wiessner *et al*.,

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[1]   Graduate School of Science and Engineering, Saitama University, Japan

[2]   Department of Civil Engineering, Faculty of Engineering, University of Peradeniya, Sri Lanka

[3]   Department of Agricultural Engineering, Faculty of Agriculture, University of Peradeniya, Sri Lanka

2005) inside the media of the wetland. Kadlec *et al.*, (2000) reported that the treatment efficiencies of CWs depend mainly on the oxidation-reduction conditions of the substrate. Operation mode is one of the main parameters that can be easily modified to improve the oxidation state of the wastewater and wetland soil. Generally, a batch operation system improves aeration of the substrate and therefore, performs better than a continuous operation system.

The oxygen concentration present in CWs is influenced by many factors, such as the organic load, mode of operation (batch, continuous, or pulse), type and development of macrophytes and water depth (Kadlec and Knight, 1996; Garcia *et al.*, 2004). Among these factors, the operation mode is one of the main parameters that can be modified to improve the oxidation state of the wastewater and wetland soil, thereby improving the removal of wastewater nitrogen and oxygen-demanding substances. Several studies have been conducted to evaluate the effects of the mode of operation on the removal efficiency of CWs.

Ammonium nitrogen is one of the principle forms of nitrogen in human waste and due to its role in water quality degradation, reducing the ammonium nitrogen concentration is an important issue. Unsuitable conditions for the removal of ammonium nitrogen can seriously limit the treatment performance of a wetland system. The addition of dissolved oxygen to wastewater can make the environment more aerobic and thereby enhance the removal activity. Several previous studies have revealed that ammonium removal in wetlands could be enhanced by batch systems and water-level fluctuations (Stein *et al.*, 2003; Tanner *et al.*, 1999) where supplemental dissolving of oxygen was noted during the water-level fluctuations.

Wetland plants can enhance NH_4-N removal, although their lower root zone oxygen limits the rate of nitrification. The aboveground organs of macrophytes contribute to the oxidation of pulse-fed wetland systems (Osorio and Garcia, 2007). Macrophytes also cause water-level fluctuations by increasing the evapotranspiration during pulsed-flow application (Osorio and Garcia, 2007). However, the effect of a pulsing feed on water quality improvement and plant growth in constructed wetlands has not been well documented.

Very few studies are available on free water surface wetlands, regarding this context in tropical regions. Therefore, this study investigated and compared two hydraulic regimes, referred to as pulsing feed (PF) and continuous feed (CF) of wastewater, in constructed wetlands. The objectives of the present investigation were to evaluate the effects of the hydraulic regime on 1) efficiency of domestic wastewater contaminant removal and 2) production of aboveground plant biomass of plants.

MATERIALS AND METHODS

Constructed wetland system

A constructed wetland was built to treat wastewater from a student dormitory at the University of Peradeniya, Sri Lanka (7°15'N 80°35'E). This system was designed to function as a surface-flow wetland. This system consisted of two units named L1 and L2. The length, width and depth of the units were 25 m, 1.0 m and 0.6 m, respectively. A gravel-based medium (depth 0.5 m) was used from top to bottom and a soil layer (depth 0.1 m) supported the vegetation. *S. grossus* L (Cyperaceae) was planted at the initial shoot density of 4 shoots m^{-2}. The inlet hydraulic retention time (HRT) was around 24 hours.

Planting

Planting of *S. grossus* L. was done in early January 2006 and the wastewater feed was started soon after planting. Two quadrates of 1 m^2 each were placed at 8 m (near the inlet) and at 16 m (near the outlet) from the inlet. The quadrate locations were used to calculate the average growth variations of *S. grossus* along the channel.

Plant sampling

Non-destructive measurements of plant growth (shoot height and shoot density) were taken at fortnight intervals within these two quadrates. For destructive analysis, plants were harvested after 6 months and their biomasses were measured. Harvesting was done twice, at 6 and 10 months after planting, after the formation of inflorescences and plant growth saturation.

System hydraulics

Wastewater was applied to one unit as CF and to the other as PF. During the PF, wastewater was applied continuously for 5 days and stopped for 2 days. The average flow rate was maintained around 8 m^3 per day for the CF and 11.2 m^3 per day for the PF to equalize the total volume of wastewater treated per week (56 m^3).

Water and soil sampling

Water samples were taken at monthly intervals from January to September 2006. Water samples were collected from the inlet and outlet into sterilized sampling bottles. Water quality parameters such as BOD_5, NH_4-N and NO_3-N were measured according to the standard methods (APHA *et al*., 1998). The soil nitrogen concentration was determined by using the total Kjeldahl method. Total phosphorous was determined by the ascorbic acid method. All statistical analyses (*t*-test) were performed by using Sigma Stat 3.11 (Systat Software Inc. 2004). P < *0.001* was considered as statistically significant.

RESULTS AND DISCUSSION

Water quality improvement in wetland systems

BOD_5 removal

Table 1 shows the removal rates of BOD_5, NO_3-N and NH_4-N in Phase I (initial development stage from planting to harvesting: January–June, 2006) and Phase II (re-growth stage after harvesting: June–September, 2006). It was noted that BOD_5 removal was lower and fluctuated during Phase I. However, when the plants had grown for three months (Phase II), the BOD_5 removal was higher and more stable.

BOD_5 removal rates were higher in the PF system than that in the CF system in both phases. The BOD_5 removal rates in the effluent of the PF unit were around 45% (Table 1) in Phase I and 53% in Phase II, whereas they were 31% and 39%, respectively in the CF system.

It can be assumed that the development of microbial biomass and establishment of plant rhizosphere and system acclimatization occurred during Phase I. Subsequently, the system was well established and showed higher BOD_5 removal during Phase II than during Phase I.

The BOD_5 of domestic wastewater tends to be dominated by readily biodegradable organic carbon with a C:N:P ratio that is amenable to biological decomposition (Merz, 2000). Treatment wetlands remove wastewater BOD_5 through biochemical and physical decomposition of organic compounds. The decomposition pathway by which wetland carbon loads are processed is determined by a balance between the carbon load and the supply of oxygen (Merz, 2000). Our PF unit had no water application for 2 days, followed by 5 days of continuous water application. This two-day resting period might have improved aeration of the substrate close to the surface. It also had improved the balance between the carbon load and oxygen supply. This two-day pulsing flow may be the reason for the significantly higher BOD_5 removal rate of the PF unit (P<0.001). In free-water surface wetlands, the microbes on media surfaces get more oxygen from the atmosphere by diffusion than from the subsurface flow wetland. This oxygen participates in the removal of the soluble carbon compounds in the wastewater (Kadlec, 1995). Therefore, free-water surface wetlands are efficient users of external carbon sources, as revealed by higher BOD_5 removal.

Nitrogen removal

The average concentrations of ammonium in the influent were 17.8 ± 10.2 mg N L^{-1} and 9.9 ± 4.0 mg N L^{-1} for Phase I and Phase II, respectively (Table 1). Ammonia volatilization depends on environmental factors such as solar energy, temperature and wind speed (Pedrazzini and Tarsitano, 1986). Phases I and II were conducted in different seasons and under different environmental conditions. Ammonia removal might also have been affected by the influent ammonium concentrations during Phases I and II. The average effluent concentrations in Phase I were 14.8 ± 9.2 and 14.6 ± 7.2 mg N L^{-1} in the CF and PF systems, respectively. During the Phase II, the respective effluent concentrations were 7.0 ± 3.2 mg N L^{-1} and 6.9 ± 3.6 mg N L^{-1} for the CF and PF systems, respectively. During Phase II, the removal efficiency increased to 29–30% compared to that in Phase I, which was 16–18%.

Table 1. Average removal of biological oxygen demand (BOD_5), nitrate-nitrogen (NO_3-N) and ammonium-nitrogen (NH_4-N) in first and second phases

Parameter	Influent	CF effluent	PF effluent
BOD_5 up to first harvest (Phase I)*	42.4 ± 4.7	29.3 ± 18.3	23.5 ± 3.6
Removal efficiency (%)		31.0	44.7
BOD_5 up to second harvest (Phase II)*	66.0 ± 15.7	40.3 ± 12.7	31.0 ± 14.8
Removal efficiency (%)		38.9	53.0
NO_3-N up to first harvest (Phase I)*	6.0 ± 2.8	3.1 ± 0.4	3.2 ± 0.5
Removal efficiency (%)		48.3	46.2
NO_3-N up to second harvest (Phase II)*	6.5 ± 2.9	4.9 ± 2.4	4.3 ± 2.3
Removal efficiency (%)		24.5	34.2
NH_4-N up to first harvest (Phase I)*	17.8 ± 10.2	14.8 ± 9.2	14.6 ± 7.2
Removal efficiency (%)		16.6	18.1
Average removal of N03 (mgl-1) from first harvesting to second harvesting			4.30
Removal efficiency (%)			34.18
NH_4-N up to second harvest (Phase II)*	9.9 ± 4.0	7.0 ± 3.2	6.9 ± 3.6
Removal efficiency (%)		29.4	30.1

Concentration values are given as mean ± standard deviation (mg L^{-1}) - *Phase I: Jan–Jun 2006 and Phase II: Jun–Sep 2006

The average concentrations of NO_3-N in the influent wastewater were 6.0 ± 2.8 and 6.5 ± 2.9 mgL^{-1} (Table 1) in Phase I and Phase II, respectively. In addition, the NO_3-N concentration did not vary much during either phase. The NO_3-N concentration was lower than that of the NH_4-N concentrations (9.9 ± 4.0 to 17.8 ± 10.2 mgL^{-1}). This result agrees with the report that wastewater generated from human waste can have significant levels of NH_4-N and organic N, but not a considerable amount of NO_3-N (Huang *et al.*, 2000).

Nitrogen removal is a combination of aerobic and anaerobic processes. Aerobic conditions are necessary for nitrification. Functioning of nitrifiers in the substrata of constructed wetlands are likely to be restricted to the surface layers of the medium and the root zone of wetland plants (Reddy and Patrick, 1984; Reddy *et al.*, 1989). The high concentrations of NH_4-N in the effluent indicate that nitrification was not limited by ammonium availability, but it may be limited by either the supply of oxygen to the substrate or the slow growth of nitrifiers in both phases in CF systems (Garcia *et al.*, 2004).

While the PF system was expected to promote aerobic soil conditions during periods without application of water, the PF application in the present study showed improved BOD_5 removal in both phases and higher NO_3-N removal in the Phase II. The higher BOD_5 removal suggested that NH_4-N was produced by decomposition of organic matter in Phase II, which contributed to the higher NH_4-N concentration in the effluent. In addition, a portion of the NH_4-N may have been converted to NO_2-N (not measured in lab due to unavailability of chemicals) and NO_3-N through nitrification in the PF system. This may be supported by the fact that there was no significant ($P<0.001$) difference in ammonium removal between the two systems. A study (without drainage) carried out by Osorio and Garcia (2007) with intermittent (applying the corresponding volume of wastewater in 20 min. per day) and continuous feeds, states, 98% ammonium removal was achieved with the intermittent system.

Better plant growth was observed in Phase II than in Phase I in the CF system. CF might have improved the NH_4-N uptake and thereby increase the removal efficiency, but no significant difference between CF and PF applications was observed for NH_4 removal during both phases. This may be due to a lag phase of microbial activity (Jamieson *et al.*, 2003). The five-month period of the first phase and the three-month period of the second phase might not be long enough to improve the aeration of the media sufficiently to enhance the NH_4-N removal. However, it seemed that these periods acted as lag periods only for NH_4-N. In contrast to NH_4-N removal, NO_3-N removal was increased during the second phase but did not show a significant difference between CF and PF systems.

Plant growth

The variations in shoot heights and shoot densities are presented in Fig. 1(A) and 1(B), respectively. The maximum heights of *S. grossus* during Phase I (the first 5 months) were 212 ± 5 and 212 ± 8 cm for the CF and PF systems, respectively. The curves also show that the shoots reached their maximum height within 13 to 15 weeks after planting. There was no significant difference between the two systems in plant height during Phase I, but differences in the aboveground growth of plants became noticeable during Phase II. The growth of *S. grossus* was most rapid during this phase. The plants reached their maximum heights of 215 ± 4 and 171 ± 5 cm for CF and PF systems, respectively, between 8 to 10 weeks after planting. The final mean shoot densities were 89 and 52 shoots m^{-2} in the CF system and 50 and 31 shoots m^{-2} in the PF system during Phases I and II, respectively. The aboveground biomass gradually declined from 1.75 to 1.60 and 0.85 to 0.75 kg m^{-2} with distance from the

inlet along the channel up to 16 m (Fig. 2) and showed a maximum of 1.9 and 1.2 kg m^{-2} near the outlet in both CF and PF systems.
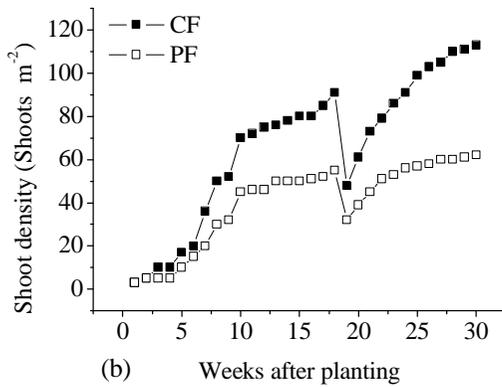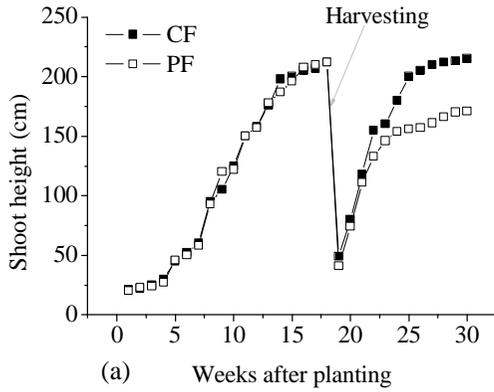

Fig. 1. Plant growth under continuous feed (CF) and pulsed feed (PF) systems
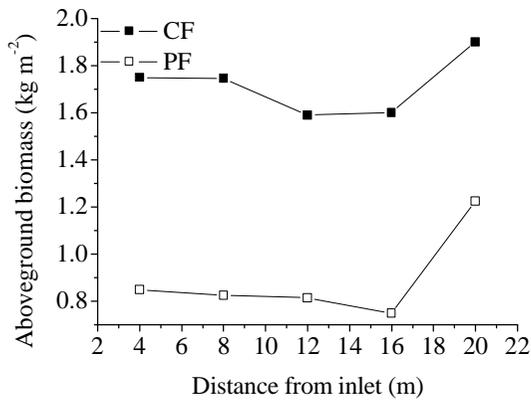(a) Mean cumulative shoot heights and (b) mean shoot densities of plants.

Fig. 2. Aboveground biomass distribution along the channel at the end of Phase

A significant ($P<0.001$) decline in shoot densities was observed in the PF system during both phases. The reasons may be water stress and the disturbance between the root surface and the water film during the pulsing application. Pulsing might reduce the nutrient uptake and thereby reduce shoot density and plant biomass. A richer nutrient condition may enhance plant productivity (Tanner, 2001), and this would be revealed by the biomass variation along the channel. The maximum seasonal aboveground biomass for *Scirpus* spp. can range between 0.4 and 1.4 kg m^{-2} in temperate regions like North America (Tanner, 2001). The maximum aboveground biomasses for *S. grossus* in this study were 1.9 and 1.2 kg m^{-2} for CF and PF applications, respectively, during the first phase. Compared to the natural conditions, here the plants got rich nutrients and consequently showed higher biomasses.
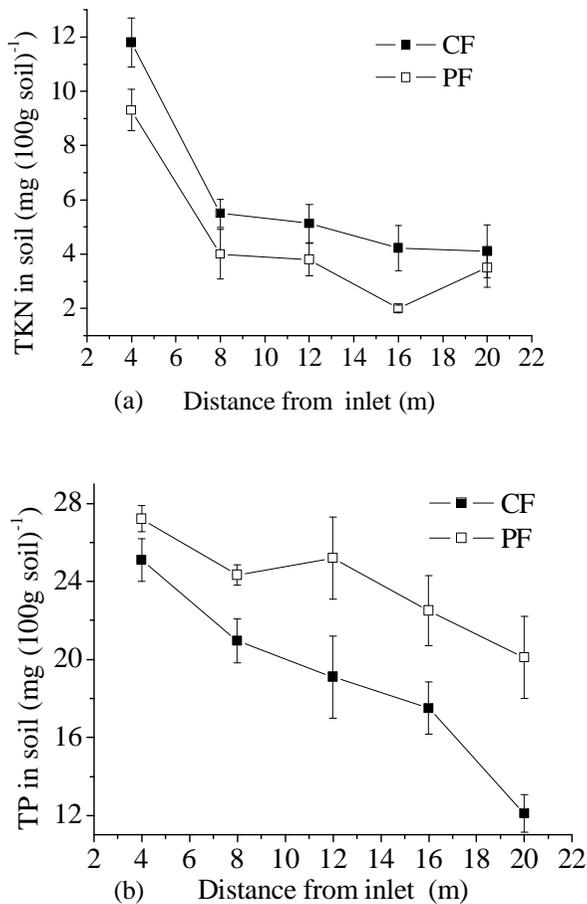

Fig. 3. **Variations in (a) total Kjeldahl nitrogen (TKN) concentrations, and (b) total phosphorous (TP) concentration in soil along the channels of continuous feed (CF) and pulsed feed (PF) systems. Concentrations are given as mean $\pm$ standard deviation**

TKN and TP in substrate

The soil was tested at a depth of 10 - 20 cm below the soil surface, which is the root zone. The TKN and TP in the soil along the channels of the two systems were examined at the end of the study period (just before the second harvesting), and the values are presented in Figs. 3(A) and (B). The highest concentrations of nitrogen (11.8 ± 0.9 and 9.3 ± 0.8 mg per 100 g soil) were near the inlet, and the lowest (4.1 ± 1.0 and 3.5 ± 0.7 mg per 100 g soil) were near the outlet in the CF and PF systems, respectively. The soil of the CF application system contained a comparatively higher concentration of available nitrogen than the soil of the PF application system. In contrast, higher available phosphorus concentrations were observed along the channel in the PF system than in the CF system. Compared with a previous study carried out by Jinadasa *et al.*, (2005), the nitrogen values were low in the sediments in the current study. They have observed nearly 0.3% nitrogen in soil sediment, but no data was available on phosphorus.

A possible reason for the lower TKN in the soil of the PF system may be the physical agitation during the flow. In the PF unit, the wastewater flow (56 m^3) was sent in over a period of five days, causing greater internal turbulence and mixing than in the CF system. The greater turbulence in the PF system allows a larger volume of water to pass through soil pores than in the CF system. A PF reaerates the surface of the soil. In addition, PF resulted in greater fluctuations of water depth than CF. These conditions might have improved the ammonium volatilization and thereby reduced the available soil nitrogen concentration in the PF system than in the CF system. In addition, both aerobic and anaerobic soil conditions are necessary for removal of nitrogen from wastewater. The discontinuous water application in the PF application creates temporal variations in the soil oxidation status (Poach *et al.*, 2007). This PF application changes the soil oxidation condition along the channel as well as inside the substrate. As a result, alternately aerobic (which induces nitrification) and anaerobic (which induces denitrification) conditions may also have reduced the available nitrogen in the PF system.

The PF application had a significant effect on available phosphorus along the channel. The disturbance in the CF was smaller than in the PF system. This condition leads to better absorption of phosphorous by the roots of plants in the CF system. Therefore, the CF system showed a lower concentration of available phosphorous in the top layer. The different trends observed for nitrogen and phosphorus concentrations in the soil may be due to different removal mechanisms. Phosphorus removal is presumed to be mainly due to physical adsorption by the media and microbial activity, whereas nitrogen removal is mainly due to microbial processes (Reddy *et al.*, 1989).

CONCLUSIONS

Pulse feeding in shallow free-water-surface in constructed wetlands is expected to provide greater oxidation compared to continuous feeding. Although the results obtained in this study under tropical conditions were dissimilar to previous studies in terms of ammonium removal, the pulse application of wastewater promoted the average BOD$_5$ removal rate of 45–53% compared with the 31–39% obtained in continuous flow system. Maximum NO$_3$-N and NH$_4$-N removal was 48% and 30% in both units, and the two treatments did not show a statistically significant difference (P < 0.001). The amounts of N were 11.8 and 9.3 mg per 100 g soil and of P were 25.1 and 27.2 mg per 100 g soil for the CF and PF systems,

respectively. A notable reduction of plant biomass production was observed during the pulse flow application compared with the continuous flow system. The results also suggest that a pulse feeding of 5 days continuous wastewater application and 2 days without feeding may not be effective for ammonium removal in free water surface wetlands. In this research only a few fluctuation systems were investigated and compared the systems performances rather than optimizing the system performances. Therefore, towards the optimization concept different fluctuation frequencies are needed to be studied.

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