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Intermittent aeration to improve wastewater treatment efficiency in pilot-scale constructed wetland

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Abstract

Forced aeration of horizontal subsurface flow constructed wetlands (HSSF CWs) is nowadays a recognized method to improve treatment efficiency, mainly in terms of ammonium removal. While numerous investigations have been reported testing constant aeration, scarce information can be found about the efficiency of intermittent aeration. This study aims at comparing continuous and intermittent aeration, establishing if there is an optimal regime that will increase treatment efficiency of HSSF CWs whilst minimizing the energy requirement. Full and intermittent aeration were tested in a pilot plant of three HSSF CWs (2.64 m^2 each) fed with primary treated wastewater. One unit was fully aerated; one intermittently aerated (i.e. by setting a limit of 0.5 mg/L dissolved oxygen within the bed) with the remaining unit not aerated as a control. Results indicated that intermittent aeration was the most successful operating method. Indeed, the coexistence of aerobic and anoxic conditions promoted by the intermittent aeration resulted in the highest COD (66%), ammonium (99%) and total nitrogen (79%) removals. On the other hand, continuous aeration promotes ammonium removal (99%), but resulted in nitrate concentrations in the effluent of up to 27 mg/L. This study demonstrates the high potential of the intermittent aeration to increase wastewater treatment efficiency of CWs providing an extreme benefit in terms of the energy consumption.

Keywords: Intermittent aeration, Ammonium removal, Nitrification/Denitrification, Constructed Wetlands, Horizontal sub-surface flow.

Introduction

Constructed wetlands (CWs) have been widely used in the last few decades (Vymazal, 2011), showing worthy efficiency in the treatment of urban wastewater, mine water, landfill leachate, industrial effluents, air-strip runoff and road runoff (Kadlec and Wallace, 2009). A favorable performance in terms of organic matter and ammonium removal, together with the low energy requirements, a minimal maintenance requirement and low operational costs are among the reasons for the wide spread implementation of the technology all over the world (García et al., 2010). Moreover, the important role of CWs as greenspace and wildlife habitat make them an appropriate alternative to conventional wastewater treatment, mainly in wild and isolated small communities.

Subsurface oxygen limitation has been identified amongst the main factors compromising contaminant removal in horizontal subsurface flow constructed wetlands (HSSF CWs) (Brix and Schierup, 1990). Such systems promote the co-existence of different redox statuses, these strongly affect the relative importance of the biochemical pathways for organic matter and nutrient removal (García et al., 2004).

Forced or active aeration, originally developed by Wallace (2001), has received increasing attention in the recent years as an efficient technique to improve removal of organic matter and reduce nitrogen species in HSSF CWs (Nivala et al. 2007; Wu et al. 2014). This technology has been employed for industrial waste streams, including contaminated groundwater (Wallace and Kadlec, 2005), coffee processing wastewater (Rossmann et al., 2013), landfill leachate (Nivala et al., 2007), airstrip deicing runoff (Higgins, 2003; Murphy et al. 2015), aquaculture (Webb et al., 2013) and livestock wastewater (Zhu et al., 2012). Recent studies highlight the efficiency of aerated systems in reducing nitrogen (Li et al., 2014), emerging contaminants (Avila et al., 2014) and greenhouse gas emissions (Maltais-Landry et al., 2009). Besides this Labella et al. (2015) showed that the reduction of the surface required by aerated systems counterbalances the investment and power consumption of aeration, resulting in similar costs for both aerated and conventional systems.

Most experiences with forced aeration however refer to continuous aeration, which has a significant energy consumption and can hamper the development of anoxic conditions (Wu et al., 2014). Anoxic conditions are needed for denitrification, which is an anaerobic heterotrophic process limited by the presence of oxygen and by the organic carbon availability (Fan et al., 2013).

In this sense, intermittent aeration controlling and adjusting the dissolved oxygen within the wetland seems to offer an effective alternative to avoid excessive aeration and achieve better total nitrogen removals. In fact, intermittent aeration provides environments of aerobic and anoxic conditions stimulating simultaneous nitrification and denitrification processes (Boog et al., 2014; Fan et al., 2013), which is considered the main N sink in CWs (Tanner et al., 2002). In spite of the promising results obtained in some recent studies (Fan et al., 2013; Zhang et al., 2010), currently scarce information on intermittent aeration is available. Moreover, continuous and intermittent aeration have not been compared yet.

The aim of this study was to determine the optimum forced aeration regime (i.e. continuous or intermittent) of HSSF CWs in order to increase treatment efficiency and reduce the energy consumption. To this end, the effect of continuous and intermittent aeration on organic matter and nitrogen removal was evaluated in pilot HSSF CWs.

Materials and Methods

Pilot plant

The experimental plant (Figure 1) was located at the Agropolis campus of the Universitat Politècnica de Catalunya·BarcelonaTech, in the municipality of Viladecans, near Barcelona, Spain (41.288 N, 2.043 E UTM). The plant was built in early 2015 and set in operation in May of the same year. The raw wastewater, coming from an office building hosting around 50 people, was treated in a septic tank and then pumped to a continuously stirred plastic tank (1.2 m^3 volume) used as a reservoir for a few hours. Afterwards, wastewater (here on referred to as influent) was pumped equally into three HSSF CWs in parallel which provided secondary treatment. The individual CW cells were built with an external steel structure supporting five composite polypropylene and glass fiber panels which form the lightweight support for a butyl rubber waterproof membrane. Each CW was built as a prototype for an autonomous reed bed installation as part of a larger project. Each CW had a surface of 2.64 m^2 (2.2 m long, 1.2 m wide, 1.3 m high). A uniform gravel layer (40% estimated initial porosity) was set to provide a depth of 1.10 m. The water level was kept at 0.10 m below the gravel surface, giving a total water depth of 1 m. The CWs were planted in April 2015 with common reed (*Phragmites australis*) at an initial density of 16 plants/m^2. The CWs were automatically fed by means of peristaltic pumps under a continuous flow regime and operated at 5.5 days of hydraulic retention time (HRT), with a surface hydraulic loading rate (HLR) of about 7.2 cm/d and a cross-sectional organic loading rate (OLR) around 8 gCOD/m^2·d. More details about the beds design and operation can be found in Table 1. During the setting-up of the system, a PVC cylinder (volume of about 0.22 m^3) was placed nearby the outlet zone of each bed in order to provide a free gravel zone.

Aeration system

Aeration was provided in each bed by means of six aeration pipes (outer diameter of 15 mm) pierced with 3 mm holes at a 305 mm separation. These parameters were selected based on typical values used in industrial settings. The system of pipes covering the bottom of the beds was connected to a compressor injecting air at a flow rate of 12.1 m^3/h (Josval Serie Cierzo NK 50, Zaragoza, Spain).

As previously done by Labella et al. (2015), dissolved oxygen at the bottom of the three wetlands was continuously monitored by means of a dissolved oxygen probe (CS512 Oxyguard Type III, Campbell Scientific Inc., USA) located in the gravel free area at the bottom of each bed and connected to a data logger (CR1000, Campbell Scientific Inc., USA).

In order to assess the effect of forced aeration on the wetlands performance, the experimental design as shown in Figure 1 was employed with

- one bed continuously aerated (here on referred to as fully aerated),
- one bed with intermittent aeration controlled by a minimum oxygen set point concentration of 0.5 mg/l (later referred to as intermittently aerated),
- one bed not aerated (referred to as the control from this point onwards).

The intermittent aeration was achieved by means of a feedback option of the data logger (control Deadbond version 2.5). The valve controlling air injection was opened when the oxygen concentration was lower than the 0.5 mg/l set point and closed for values higher than this. This configuration was established in accordance with previous results showing that wastewater treatment was satisfactorily improved when oxygen concentration within the wetlands was maintained at 0.5 mg/L (Labella et al., 2015).

Physical and Chemical analysis

Water quality was monitored during twelve weeks (between May and July 2015) collecting 27 samples from CWs influent (effluent of the stirred plastic tank) and 27 samples from the CWs effluent. The surveyed water quality parameters were the total chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), ammonium nitrogen (NH_4^+-N), nitrite (NO_2^-N) and nitrate (NO_3^-N) nitrogen. Analyses were carried out according to Standard Methods (APHA-AWWA-WEF, 2005) 5220 for COD and4500 for TKN. Ammonium was measured according to the Solorzano method (Solorzano, 1969), while nitrites and nitrates were determined by a DIONEX ICS-1000 ion chromatograph (limit of detection 0.5 ppm NO_x). COD and ammonium nitrogen were monitored two or three times per week, while the others parameters were analyzed weekly.

For each configuration, the removal efficiencies were calculated for nitrogen species and COD according to Eq. 1.

$$\text{Removal efficiency } (\%) = \left(1 - \frac{Ce*Ve}{Ci*Vi}\right) * 100 \qquad \text{Eq. 1}$$

Where *Ce* was the effluent concentration, *Ve* is the effluent volume, *Ci* was the influent concentration and *Vi* the influent volume of the wetlands. The statistical difference of the experimental results was evaluated by means 3 ways ANOVA and *post-hoc* test (Tukey's) performed using SPSS statistic software 22 (IBM Corporation, Armonk, New York, USA).Water temperature was continuously monitored by means of probes (Temperature Probe Model 107, Campbell Scientific Inc., USA) located in the gravel free area at the bottom of each bed and connected to a data logger (CR1000, Campbell Scientific Inc., USA). Meteorological data were gathered from the municipal meteorological stations of Viladecans, Barcelona, Spain, located near the site.

In order to measure the evapotranspiration, the water flow was measured at the inlet and at the outlet of each wetland by means of peristaltic pumps (at the inlet) and a flow meter device located at the outlet.

Results and discussion

The dissolved oxygen concentration recorded in the three beds clearly displays the effect of aeration (Figure 2). In the bed without air injection, oxygen concentrations were always near to zero, while in the bed with intermittent air injection (0.5mg/L) oxygen concentrations ranged between 0.5 and 2 mg/L (due to the excess power of the compressor used for air injection). The oxygen concentration in the fully aerated bed was significantly higher, fluctuating between 7 and 8 mg/L.

The average air temperature during the experiments was 24.7°C, ranging between minimum values of 10.5°C and maximum values of 34.6 °C. In accordance with the summer season in Spain, water temperatures within all the CWs varied between 21°C and 32°C.

The average COD influent concentration was 118±62 mg/L, with spot peaks of 300 mg/L (Table 2). COD removal was clearly observed in the three beds, where the average discharge concentrations were 68±14 mg/L and 53±12 mg/L in the intermittently and fully aerated beds respectively; and 61±14 mg/L in the control bed. Such values correspond to similar mass removals in all the beds (61-65%). Indeed, no significant differences were recorded between the systems. The small differences observed are likely due to the low loading of the beds. Similar results were found by Butterworth et al. (2013) where the authors did not find differences between fully aerated beds and control beds without aeration. Concerning intermittent aeration, Fan et al. (2013) and Zhang et al. (2010) show scarce or a slightly positive effect on organic matter removal in synthetic and domestic wastewater.

Total Kjeldhal Nitrogen (TKN) (data not shown) saw influent concentrations ranging between 10 and 40 mg/L. Such low concentrations are attributed to the limited use of the office building, only frequented during working hours. Outlet concentrations of 10-15 mg/L were found in the bed without aeration. On the other hand, when air was injected, concentrations were reduced to about 3 mg/L. Results indicated significantly higher removals in the beds with full (76%) and intermittent aeration (77%) with respect to the control bed, in which only 54% of the TKN was removed. This suggested that the set point of 0.5 mgO_2/L was sufficient for optimal TKN removal and even more efficient than the use of full aeration.

Similar results were obtained for ammonium (Figure 3). In this case, the effluents of the aerated beds showed significantly lower concentrations than the control bed ($p<0.01$). In general, concentrations of 15±11 mg/L present in the influent were reduced to 7±3 mg/L in the bed without aeration, while values near to zero were obtained in both the partially and continuously aerated beds (Table 3). Indeed, no significant differences were found between full and intermittent aeration indicating good nitrification performance in both systems. In general, low removals found in the control (53%) were significantly increased by full (99%) and intermittent aeration (99%). The scarce ammonium removal obtained in the control bed might be attributed to the poor nitrification occurring in anoxic conditions. Such results are confirmed by previous studies in which ammonium removals increased from 59% in a control bed without aeration to 99% in a fully aerated bed (Butterworth et al., 2013). Likewise, Fan et al. (2013) and Zang et al. (2010) showed the positive effect of intermittent aeration on ammonium removal, improving removals from 20-24% in a control bed to 89-93% in an intermittently aerated bed.

The concentrations of nitrogen oxides (NO_x) provide a useful assessment of the efficacy of the nitrification and denitrification processes (Figure 4). The influent presented with relatively high concentrations of nitrate (8±4 mg/L). Concentrations found in the effluent of the fully aerated bed (24±6 mg/L) were higher than those of the intermittently aerated one (14±6 mg/L), while lower concentrations were found in the control (5±3 mg/L). Such results indicated the high contribution of aeration to the nitrification process, which results in high nitrate concentration. The results of this study are in accordance with the pattern previously showed by Maltais-Landry et al. (2009) comparing fully aerated and non-aerated beds. The authors detected net NO_x productions of about 4 mg/L in the fully aerated systems, while no NO_x was produced in the control. Further investigation of this effect will need to be undertaken on a system with less variation around the 0.5mg/l set point to maximise the creation of zones of varying oxygen concentration.

Considering the total nitrogen (TN) as the sum of TKN, nitrite and nitrate (Figure 5), intermittent aeration can achieve lower effluent concentrations (18±7 mg/L) than full aeration (27±6 mg/L). In term of removals, the control reached 61%, while, due to the high amount of nitrate, the fully aerated bed only reaches 50%. The intermittently aerated bed shows better performance, obtaining an average removal of 66% over the experimental period. Our results are in accordance with the literature, with a previous study showing 49% higher TN removals in intermittent aerated beds than in the control (Zhang et al., 2010), while others authors do not detect differences between fully aerated and control beds (Maltais-Landry et al., 2009).

It is important to highlight that, even if TN removals were similar for the aerated and non-aerated systems, in the control bed the nitrogen was mainly present in form of ammonium. In this sense, aeration is important for ammonium removal, which is much more harmful for the environment than the other nitrogen forms. Indeed, ammonium toxic effect on zooplankton community has been widely reported (Ankeley et al., 1995; Monda et al., 1995; Puigagut et al., 2005). According to the results found in this study, partial aeration is the most useful option to remove ammonium, nitrate and nitrite due to reduced energy costs over the proven benefits of continuous aeration. This is most likely due to the fact that intermittent aeration provided the coexistence of aerobic and anoxic conditions, stimulating the simultaneous occurrence of nitrification and denitrification. Indeed, a previous study found high removals of ammonium and total nitrogen, demonstrating that the intermittent aeration enhanced the growth of both ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB) (Fan et al. 2013).From an environmental and economical point of view, it is significant to highlight the extreme benefit provided by intermittent aeration in terms of the energy consumption of the system. In this study, considering 24h energy consumption of the compressor (1.5 kWh), 13.6 kWh/m^2·d were consumed by full aeration. On the other hand, the intermittent aeration only needs 8 pulse per day, corresponding to around 20 minutes of aeration (Supplementary Material, Figure 1), thus only 0.18 kWh/m^2·d were required, resulting in seventy-fold reduction in power usage. Such a short aeration time can be attributed to the fact that the air pump was probably oversized for the treatment bed being aerated, altogether with the low concentration of both COD and ammonia in the influent.

Besides this it should be taken into account that this is a preliminary study, conducted during 3 months along the start-up phase of the system. During this period macrophytes were not well stablished due to the fact that the experiment was performed during the first growing season. Therefore, the effect of the aeration strategy under well-developed macrophytes remains unknown and shall be further addressed. A longer study would be required to confirm the results collected in this study and to better characterize the observed behavior. A year-round study would be recommended in order to test the seasonal effect of aeration on nitrogen removal.

Conclusions

In this study we have tested different forced aeration regimes in a three bed pilot plant in order to improve wastewater treatment in HSSF CWs. The three beds were fully aerated, intermittently aerated to a set point of 0.5mg/l and unaerated all of which reached satisfactory performance in term of wastewater treatment. Due to the coexistence of aerobic and anoxic conditions, the intermittent aeration was the most effective solution, reaching the highest COD (66%), ammonium (99%) and total nitrogen (79%) removals. Continuous aeration promotes almost complete ammonium removal, but resulted in nitrate concentrations in the effluent up to 27 mg/L. The intermittent aeration strategy represents an effective and energy efficient means to reduce ammonium concentration and indeed for general wastewater quality improvement over both fully aerated and unaerated systems.

Acknowledgements

The research leading to these results has received funding from the European Union's Seventh Framework Programme managed by the REA – Research Executive Agency http://ec.europa.eu/research/rea (FP7/2007_2013) under project reference 606326. The work has been supported by the following partners: Lab-Tools Ltd. (UK), OxyGuard International A/S (Denmark), TechnoSAM SRL (Romania). For further information on the ARBI modules and for the latest updates, please see the project website at http://arbi-eu.com/. The authors would like to acknowledge Ian Domingo and José Luis López for their help during experiment deployment.

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Tables and figures

Table 1. Technical data of the domestic wastewater wetlands

Parameter	Value
Dimensions (WxLxH) (cm)	120 x220x130
Water level (cm)	100
Surface area (m^2)	2.64
Flow (L/d)	190
Surface hydraulic loading rate (cm/d)	7.2
Hydraulic retention time (d)	5.5
Cross-sectional organic loading rate ($gCOD/m^2\cdot d$)	7.8
Surface organic loading rate ($gCOD/m^2\cdot d$)	8.5

Table 2. Influent and effluents concentrations of Chemical Oxygen Demand (COD) in the three wetlands along the experiment (±s.d.).

Day of experiment	**COD concentration (mgO$_2$/L)**			
	Influent	**Full**	**Intermittent**	**Control**
0	58 ± 10	63 ± 23	-	58 ± 6
5	42 ± 6	70 ± 19	-	36 ± 9
7	189 ± 12	77 ± 7	-	61 ± 7
12	118 ± 26	89 ± 10	65 ± 1	57 ± 21
14	162 ± 3	58 ± 11	53 ± 9	62 ± 8
19	145 ± 10	53 ± 10	65 ± 3	35 ± 10
21	122 ± 13	76 ± 18	61 ± 10	93 ± 7
26	115 ± 19	102 ± 6	64 ± 17	54 ± 4
28	102 ± 6	66 ± 4	74 ± 6	73 ± 7
33	100 ± 5	72 ± 4	59 ± 3	51 ± 3
35	68 ± 10	58 ± 17	44 ± 12	52 ± 13
38	72 ± 22	48 ± 5	57 ± 11	53 ± 14
42	121 ± 12	100 ± 9	73 ± 6	81 ± 11
45	102 ± 7	64 ± 5	53 ± 5	57 ± 3
47	99 ± 18	71 ± 4	43 ± 5	55 ± 9
49	136 ± 8	82 ± 14	48 ± 23	65 ± 6
52	87 ± 13	61 ± 4	55 ± 5	63 ± 3
54	125 ± 9	60 ± 13	72 ± 7	94 ± 6
56	124 ± 7	55 ± 8	55 ± 7	61 ± 6
59	71 ± 6	48 ± 3	38 ± 0	49 ± 2
61	89 ± 6	49 ± 9	47 ± 9	51 ± 8
63	71 ± 7	55 ± 7	53 ± 4	82 ± 2
66	286 ± 111	85 ± 4	29 ± 5	66 ± 13
68	83 ± 1	-	29 ± 15	47 ± 9
70	78 ± 5	67 ± 4	47 ± 8	53 ± 13
73	319 ± 9	67 ± 8	40 ± 6	59 ± 20
75	108 ± 13	69 ± 15	51 ± 12	67 ± 8

Table 3. Influent and effluents concentrations of ammonium, Total Kjeldhal Nitrogen and organic nitrogen in the three wetlands.

Day of experiment	**NH_4^+-N (mg/L)**				**TNK (mg/L)**				**N org (mg/L)**			
	Influent	**Full**	**Intermittent**	**Control**	**Influent**	**Full**	**Intermittent**	**Control**	**Influent**	**Full**	**Intermittent**	**Control**
19	19.45	0.02	0.03	7.67	32.30	2.80	2.80	11.20	12.85	2.78	2.77	3.53
26	14.19	0.03	0.03	13.33	17.20	2.80	-	14.90	3.01	2.77	-	1.57
33	5.80	0.01	0.02	5.68	11.20	3.50	4.20	9.80	5.40	3.49	4.18	4.12
47	7.40	0.08	0.08	3.11	25.30	9.10	3.50	9.80	17.90	9.02	3.42	6.69
54	28.46	0.52	1.06	6.78	38.60	2.80	7.00	14.80	10.14	2.28	5.94	8.02
61	3.07	0.01	0.02	7.31	9.80	2.80	2.80	16.90	6.73	2.79	2.78	9.59
68	0.78	0.01	0.01	4.89	9.80	3.50	2.80	13.30	9.02	3.49	2.79	8.41
75	3.40	0.00	0.01	3.08	9.80	2.80	2.80	7.00	6.40	2.80	2.79	3.92

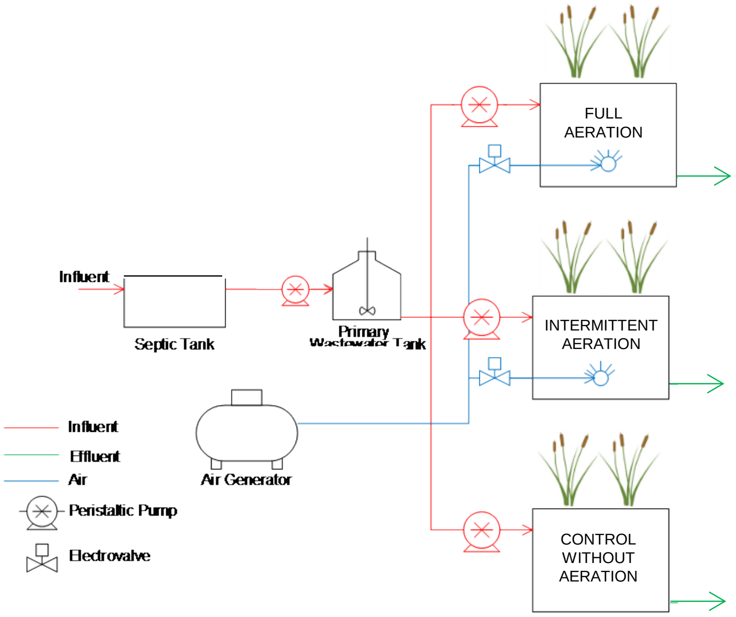

Figure 1. Diagram of the experimental plant. From the septic tank, wastewater was pumped into a storage tank and conveyed to the three wetlands beds.

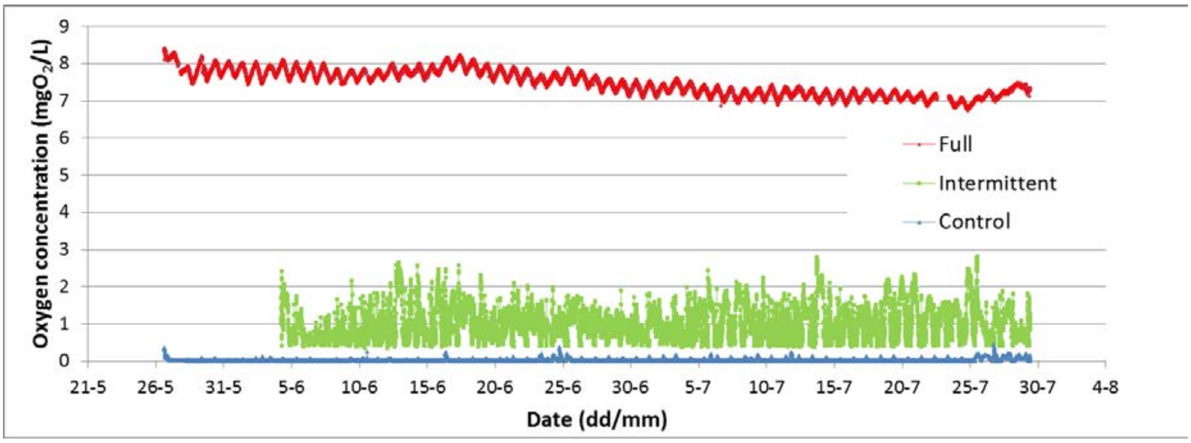

Figure 2. Dissolved oxygen concentration in the three beds used to treat domestic wastewater over the course of the experiment.

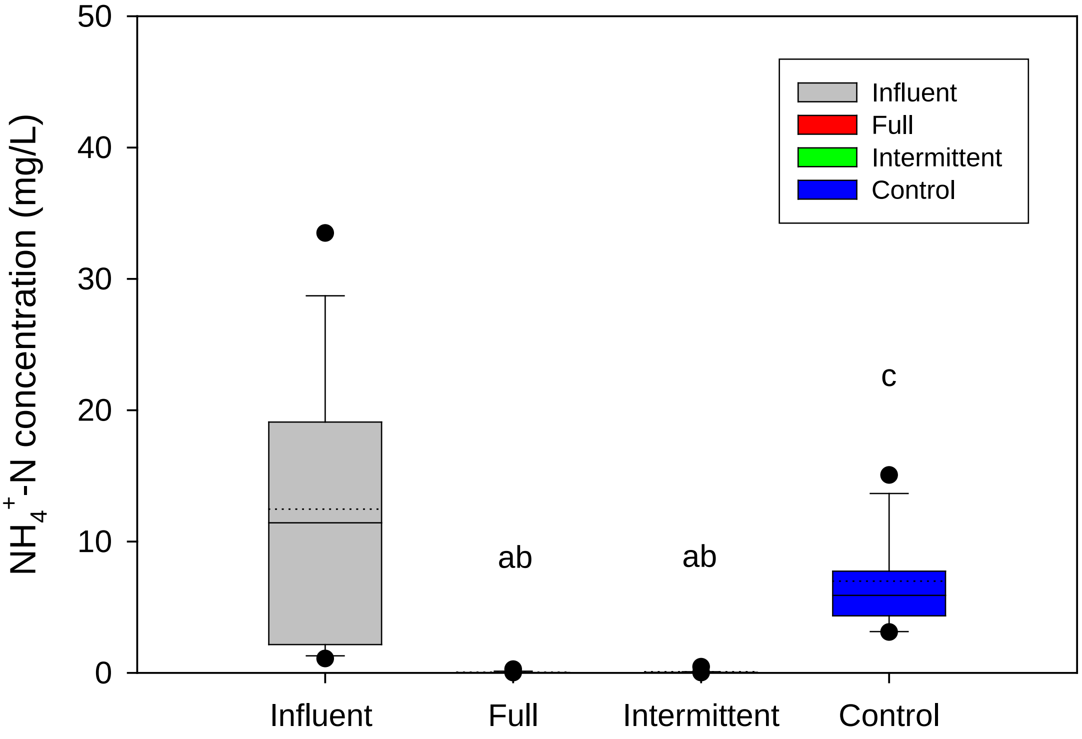

Figure 3. Influent and effluents concentrations of ammonium in the three wetlands (n=27). The lower boundary of the box indicates the 25th percentile, the lines within the box mark the median (solid line) and the average (dotted line), and the upper boundary of the box indicates the 75th percentile. Whiskers (error bars) above and below the box indicate the 90th and 10th percentiles, respectively. Upper and bottom dots represent the 95th and 5th percentile, respectively. Letters indicate which groups of data differ with significance, *p*<0.01.

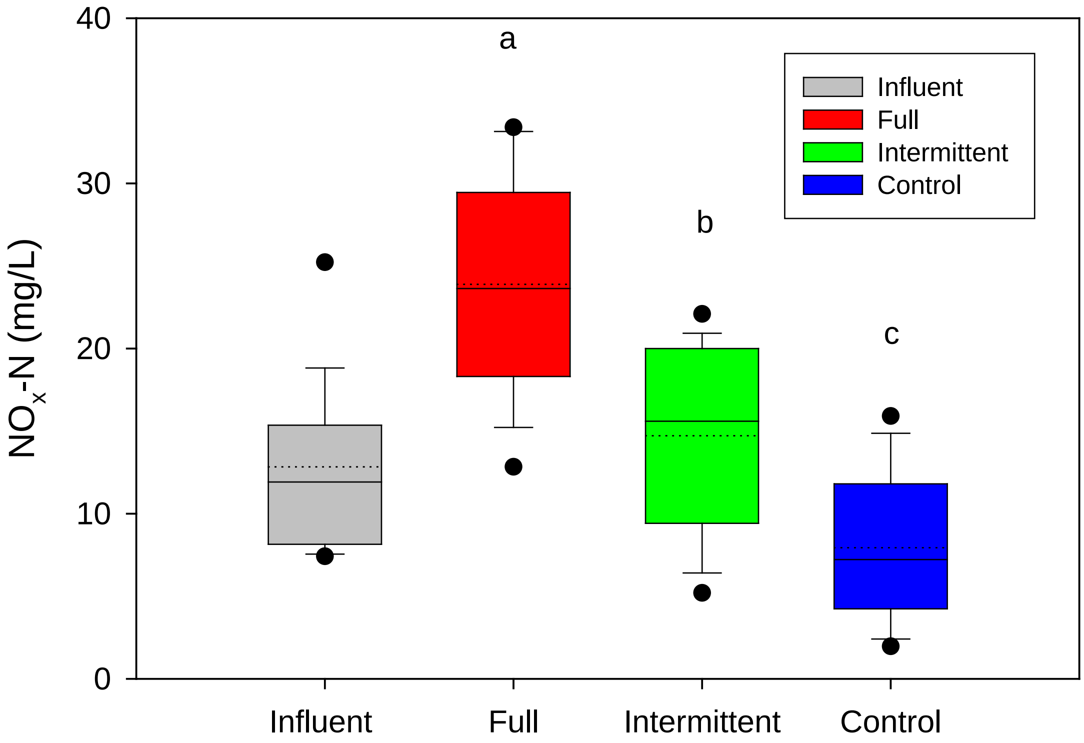

Figure 4. Influent and effluents concentrations of nitrite and nitrate in the three wetlands (n=27). The lower boundary of the box indicates the 25th percentile, the lines within the box mark the median (solid line) and the average (dotted line), and the upper boundary of the box indicates the 75th percentile. Whiskers (error bars) above and below the box indicate the 90th and 10th percentiles, respectively. Upper and bottom dots represent the 95th and 5th percentile, respectively. Letters indicate which groups of data differ with significance, *p*<0.01.

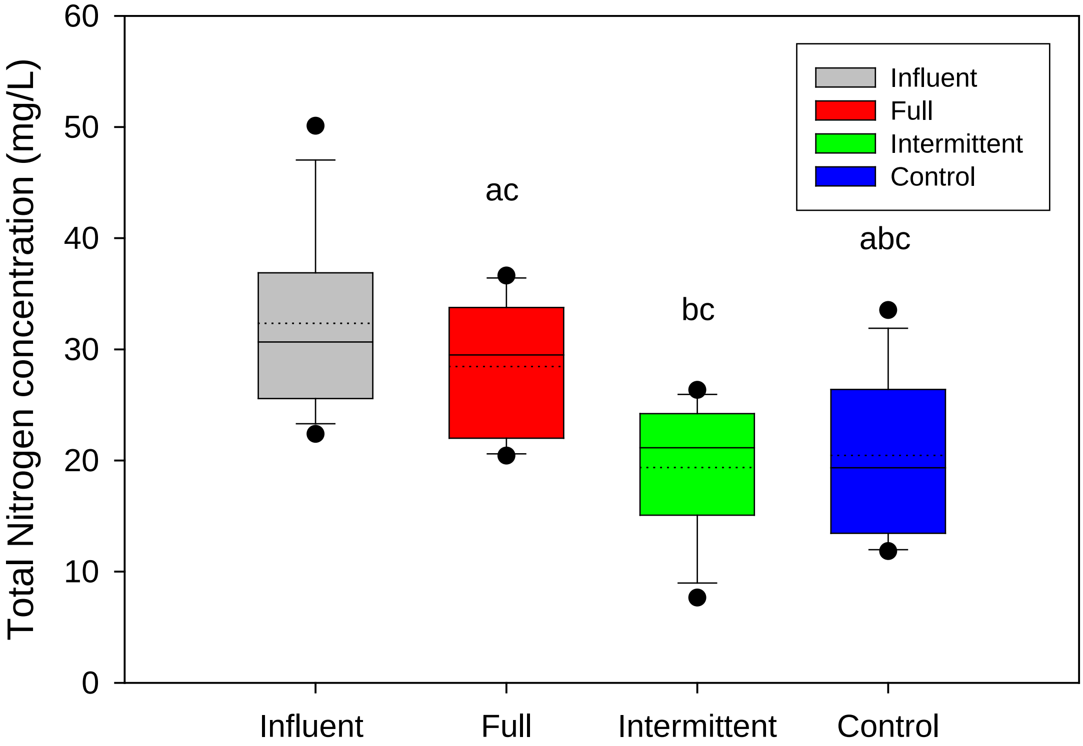

Figure 5. Influent and effluents concentrations of total nitrogen in the three wetlands (n=27). Total nitrogen is calculated as the sum of TKN, nitrite and nitrate. The lower boundary of the box indicates the 25th percentile, the lines within the box mark the median and the average (dotted line), and the upper boundary of the box indicates the 75th percentile. Whiskers (error bars) above and below the box indicate the 90th and 10th percentiles. Upper and bottom dots represent the 95th and 5th percentile, respectively. Letters indicate which groups of data differ with significance, *p*=0.012.

Supplementary Material

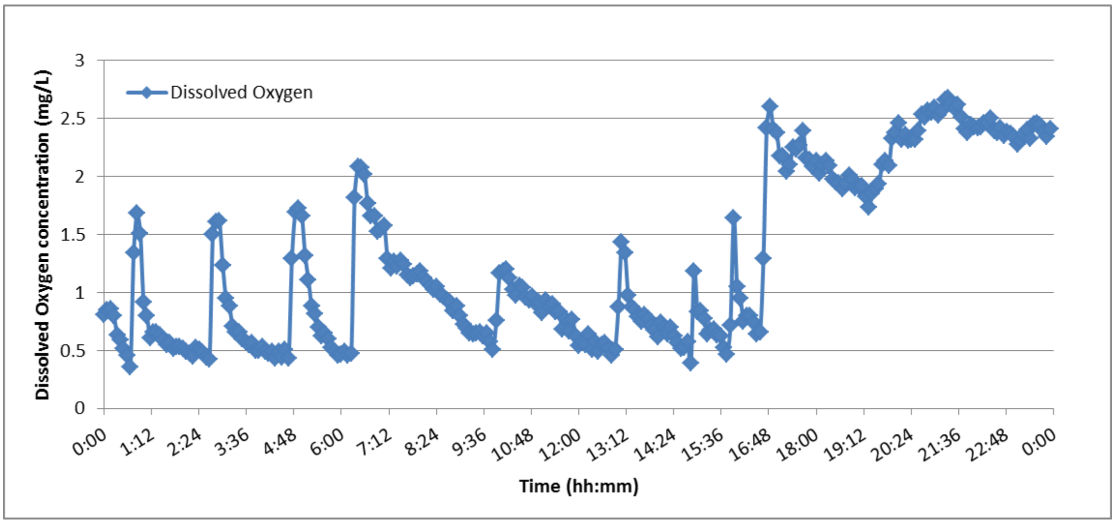

Figure 1. Data of dissolved oxygen collected in the bed with intermittent aeration along one day.