Aeration and heating to improve treatment efficiency and delay clogging development of intensified experimental constructed wetlands

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Abstract

Intensive constructed wetlands including forced aeration and heating were studied to improve treatment efficiency and prevent clogging. The experiments were carried out in a pilot plant (0.4 m^2) treating urban wastewater with an organic loading rate of 40-60 $gCOD/m^2 \cdot d$. Continuous and intermittent aeration was performed on 8% of the wetland surface, leading to different dissolved oxygen concentrations within the wetlands (from 0.2 to 5 mgO_2/L). Continuous forced aeration increased organic matter (COD) and ammonium nitrogen removal by 56% and 69%, respectively. Improvements in wastewater treatment caused by forced aeration can result into reduction of the surface area. This work demonstrated that for the studied configuration the cost of the power consumption of the continuous aeration was largely covered by the reduction of the wetlands surface. Even if the heating of 8% of the wetland surface at 21°C had no effects on treatment performances, positive results showed that solids accumulation rate within the granular medium, which is closely related to the development of clogging. It has been demonstrated that heating for 10 days per year during 20 year period would delay the equivalent of 1 year of solids accumulation.

Keywords: Artificial aeration, Heating, Wastewater treatment, Clogging, Constructed Wetlands.

Introduction

Constructed wetlands (CWs) are widely used for the treatment of wastewater including urban wastewater, mine water, landfill leachate, industrial effluents, air-strip runoff and road runoff (Kadlec and Wallace, 2009). A favorable performances 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). Due to the relatively larger surface requirements in comparison to the conventional treatment systems such as activated sludge, CWs are particularly suitable for small communities (< 2,000 population equivalent (PE)) (Rousseu et al. 2004; Puigagut et al. 2007).

In horizontal subsurface flow constructed wetlands (HSSF CWs) the water, maintained at a constant depth, flows horizontally below the surface of a granular medium planted with emergent rooted wetland vegetation such as *Phragmites australis* (common reed) or *Typha latifolia* (cattail). In such systems contaminants are removed thought a number physical, chemical, and biological processes taking place simultaneously (García et al., 2010).

In recent years research in HSSF CWs has focused on the improvement of treatment performances, as well as on the prevention of clogging phenomenon and on the understanding of fundamental processes occurring in wetlands (García et al., 2010).

CWs are characterized by the simultaneous co-existence of areas with different redox status that influences the contaminant removal. The redox conditions strongly affect the relative importance of the different biochemical pathways for removing organic matter (García et al., 2004, 2005). Since HSSF CWs are generally considered to be anaerobic, organic matter oxidation and nitrification may be enhanced by promoting more oxidized conditions (Caselles-Osorio and García 2007).

The heterogeneous distribution of redox conditions in HSSF CWs is caused by several factors including the presence of plants and fluctuations in the water level due to evapotranspiration. Redox potential decreases with depth with higher redox present in the upper zone of the bed (5–20 cm) due to plant oxygen release and passive oxygen diffusion from the atmosphere (Faulwetter et al. 2009).

Among the strategies to increase CWs performances forced (or active) aeration has been recently suggested as an efficient way to improve removal of organic matter and reduced nitrogen species (Nivala et al. 2007; Wu et al. 2014).

Since the ‘90s active aerated systems have shown interesting results leading to a more than ten-fold increase in the removal rates compared to passive systems (Nivala et al., 2013). A laboratory-scale study has indicated that aeration has a certain effect on the solids degradation rates, increasing the amount of accumulated total organic suspended solids against the mineral fraction (Chazarenc et al., 2009).

In spite of the advantages of aeration the costs increase should be taken into account as CW ordinarily have a low operating cost. Most of the studies on forced aeration referred to “continuous aeration mode” (i.e. 24 h per day) which has a significant energy consumption. Moreover, this option can lead to a contradiction between the removal of ammonium and total nitrogen because of the lack of favourable anoxic conditions for denitrification (Wu et al., 2014). Important improvements could be achieved with intermittent aeration where the level of aeration could be adjusting and controlled (i.e. adjusting the dissolved oxygen within the wetland) and excessive aeration could be avoided. In this case intermittent aeration has been shown to achieve high total nitrogen removal by providing alternate aerobic/anoxic conditions for the simultaneously occurring nitrification and denitrification (Boog et al., 2014).

The higher contaminant removal rates achieved in forced aerated CWs might lead to a significant surface reduction. Therefore, the aeration is only justified when its costs are counterbalanced by the reduction in the capital cost derived by the decrease of the wetland size (Kadlec and Wallace, 2009).

Apart from the efficiency in pollutant removal, the clogging of the porous medium is among the main operational problems of HSSF CWs. Clogging may result in hydraulic malfunction associated to reduced treatment performance due to preferential water flows, dead zones and short circuits. Clogging affects the longevity of the systems, indeed the original life span prediction were in the order of 50–100 years (Conley et al., 1991) whereas experimental evidence has shown lifetimes of 8 years (Griffin et al., 2008).

Clogging has been widely studied during recent years (Knowles et al., 2011; Nivala et al., 2012). It is well known that clogging is caused by the accumulation of materials associated with treatment. The quantity and composition of the clog matter may vary but typically consists of highly hydrated gels and sludge with inorganic (e. g. solids from chemical erosion of gravel) and organic solids (e.g. biomass growth, plant roots, biofilm and plant detritus) (Knowles et al., 2011; Pedescoll et al., 2011).

According to Nivala et al. (2012) two strategies have been studied to manage clogging: i) preventative strategies that are aimed at delaying or minimizing the negative effects associated with clogging, and ii) restorative strategies for systems exhibiting clogging-related hydraulic problems or poor treatment efficiency. Preventative strategies include better management practices, inlet and loading adjustments, and changes to hydraulic operating conditions (including intermittent operation, backwashing and/or reversing the direction of flow). Restorative strategies include the excavation of dirty gravel and replacement with new media; excavation, washing, and reuse of gravel; direct application of chemicals to the gravel bed; and most recently, the application of earthworms to the system (Nivala et al., 2012).

Management of CW with regards to clogging can be aided significantly with an accurate gauge of the clog state. A number of methodologies for monitoring the clogging have been developed with hydraulic conductivity measurement or tracer tests being popular (Pedescoll et al., 2009). While useful these techniques cannot provide real-time information about the health of the system. A new technique has been developed in recent years that utilizes magnetic resonance techniques (Morris et al. 2011; Hughes-Riley et al. 2014) that allow for real-time collection of information. This is particularly useful for the creation of an Automated Reed Bed Installation (ARBI), which this work was conducted as part of. This initiative (funded by an EU FP7 grant) is to create a wetland module where environmental factors can be changed based on input for an array of sensors with the hopes of extending bed lifetime and efficiency. The work presented in this article was conducted to further this goal by better understanding the optimal conditions for a wetland of this scale.

In general, an efficient strategy to avoid or reduce clogging should be based on the reduction of the organic matter accumulated within the porous medium. In this context, the increase of the temperature within the CW may enhance the organic matter oxidation (Garfì et al., 2012; Kirschbaum et al., 2004) increasing the concentration of the dissolved organic matter in the interstitial water (Wang et al., 2014).

This study had two main objectives, to assess the economic suitability of forced aeration in HSSF constructed wetlands and to study the effect of heating on the longevity of HSSF constructed wetlands.

Materials and Methods

Pilot plant

The experimental plant was located in Barcelona (Spain) at the Department of Hydraulic, Maritime and Environmental Engineering of the Universitat Politècnica de Catalunya·BarcelonaTech. The plant was set in operation in March 2011. Wastewater was pumped from a municipal sewer where it was then screened and subsequently stored for approximately 5 h in a continuously stirred plastic tank (1.2 m^3 volume). The primary treatment consisted of a hydrolytic upflow sludge bed reactor (HUSB) with 3h of hydraulic retention time (HRT). The primary treatment was followed by two HSSF CWs in parallel acting as secondary treatment. Each CWs was made of a PVC container with a surface of 0.4 m^2 (0.75 m long, 0.55 m wide, 0.39 m high). A uniform gravel layer (40% initial porosity) was used which provided a wetland depth of 0.35 m. The water level was kept at 0.05 m below the gravel surface to give a water depth of 0.30 m. CWs were planted with common reed (*Phragmites australis*) at an initial density of 16 plants/m^2.

Both CWs were fed under continuous flow regime and operated at 0.8 days HRT, hydraulic loading rate (HLR) of about 160 L/m^2·d and an organic loading rate (OLR) ranging from 40 to 60 gCOD/m^2·d.

CWs effluent was discharged into a graduated tank with a capacity of 22 L. Measuring the influent and effluent flow allowed for the calculation of the wetland efficiency on a mass balance basis.

Physical and Chemical analysis

Water quality was monitored from influent and effluents samples twice a week from November 2013 to May 2014. The surveyed water quality parameters were the total chemical oxygen demand (COD), ammonia nitrogen and nitrate nitrogen. Analyses were carried out according to Standard Methods (APHA-AWWA-WEF, 2005).

Aeration experiment

In order to assess the effect of forced aeration on wetlands performances, from November 2013 to February 2014 one of the CWs (named “experimental CW” henceforth) was equipped with an aeration system whereas the other wetland (control) operated under normal saturated passive conditions.

The aeration system consisted of a pierced resin pipe of about 50 cm long, rolled at the bottom of the wetland at its central zone. The aeration roll occupied a surface of 0.03 m^2, which corresponded to 8% of the total bed surface. The air was injected by means of an air pump working at a flow rate of 720 L/h.

Dissolved oxygen within the both of the CWs was continuously monitored by means of a dissolved oxygen probe (CS512 Oxyguard Type III, Campbell Scientific Inc., USA) connected to a data logger (CR1000, Campbell Scientific Inc., USA).

At the beginning of the experiment air was continuously injected (24 h/d), reaching an oxygen concentration within the bulk liquid of 5 mg/L. Afterwards, in order to have an intermittent aeration, the oxygen concentration within the bed was controlled by means of a control program of the data logger (control Deadbond version 2.5). This program worked according to oxygen concentration set points. The valve controlling air injection was opened when the oxygen concentration was higher than the set point and airflow stopped when the set point concentration was reached. Thus, after 9 days of continuous aeration the oxygen concentration within the bed was set at 3 mg/L and successively reduced to 1.5, 0.5 and 0.2 mg/L in order to test the treatment performances at different aeration rates. The aeration configuration and the control system were able to constantly provide the pre-established oxygen concentrations within the bed.

For each configuration, the removal efficiencies of the experimental wetlands with respect to the control wetland were calculated for NH_4^+-N and COD according to Eq.1.

$$Removal\ efficiecy(\%) = 1 - \frac{Ce}{Cc} * 100 \qquad \text{Eq. 1}$$

Where Ce was the effluent concentration of the experimental wetland (in mg/L) and Cc was the effluent concentration of the control wetland. The statistical significance of the experimental results was evaluated by the repeated measures ANOVA test using R statistics software.

The oxygen consumption rate (OCR) was calculated in accordance with Eq. 2 (adapted from Cooper et al. 2005).

$$OCR = \frac{[1.0(\Delta MBOD5) + 4.3(\Delta MNH4 - N)]}{A} \qquad \text{Eq. 2}$$

Where A was the area of the bed (in m^2); ΔM_{BOD5} (here calculated from the relation BOD_5/COD=0.7 indicated by Metcalf and Eddy, 2003) and $\Delta M_{NH4\text{-}N}$ were the differences of BOD_5 and NH_4^+-N mass removed in the experimental wetland with respect to the mass removed in the control.

Data was used to compare the cost of the aeration in each configuration in order to assess the viability of the intensive aeration (Table 1). Three wetlands sizes were considered for this study, corresponding to 100, 500 and 1,000 (PE). This study was carried out considering a wetland located in Spain and a wetland located in the United Kingdom. For each CW, the annual cost was calculated including construction and maintenance considering a 20 year amortization period. The costs of the Spanish CW were calculated using information provided by Ortega et al. (2010), while data for the CW costs in United Kingdom were provided by ARM Ltd (Rugeley, UK). The electric consumption (Table 2) was calculated according to data gathered from the experiments carried out in the pilot plant.

Heating experiment

In order to test the effect of temperature on CWs, from March to May 2014, a heating system (Wave 300 W) was introduced into the center of the experimental wetland, with a temperature set to 21°C. As for aeration, the removal efficiency of the experimental wetlands was calculated with respect to the control wetland for COD (Eq. 1).

Concerning clogging, a calculation was made to estimate the delay of solids accumulation rate heating 8% of the wetland surface during 10 days.

Reduction of solids accumulation was estimated starting from the difference of COD concentrations in the experimental and control wetlands and considering the correlation between volatile suspended solids (VSS) and COD (VSS/COD = 0.84) (Caselles-Osorio and Garcia, 2007)): From this the amount of VSS removed from the experimental wetland was calculated. Subsequently, considering different VSS/TSS ratio summarized in Table 3, a calculation of the released total suspended solids (TSS) retained within the gravel was made. From these values it was possible to estimate the delay on the annual solids accumulation rate. All calculations were based on data from different full-scale constructed wetlands found in literature. In accordance with our experimental set-up in all cases we considered the heating of 8% of the bed surface during 10 days per year.

Results and discussion

Aeration as a strategy to reduce the beds' surface

The aeration at different set points entailed significant increment of dissolved oxygen within the wetland, and a consequent increase in COD and NH_4^+-N removal ($p<0.05$). As shown in Figure 1, for a COD concentration of 400-300 mgO_2/L in the inlet a decrease to 160-140 mgO_2/L at the outlet was observed in the control bed, whereas lower values (about 70 mgO_2/L) were reached in the effluent of the beds with oxygen concentration set at 5, 3, 1.5 and 0.5 mg/L. Conversely, the COD concentration in the effluent of the two beds were similar when the aeration set point was 0.2 mg/L. The differences between the COD concentration in the effluents of the two beds decreased from 80 to 40 mg/L when the aeration set point was 0.5 mg/L, while almost no differences between the systems was observed when the set point was 0.2 mg/L was set as the aeration set point. On the whole, aeration increased COD removal by 56%, 46%, 40%, 35% and 3% for 5, 3, 1.5, 0.5 and 0.2 set points, respectively.

Concerning ammonium nitrogen (NH_4^+-N) (Figure 2), differences between systems with and without aeration were even more evident. Ammonia nitrogen concentrations in the influent ranged between 14 and 32 mgNH_4^+-N/L due to variations in the wastewater quality. The concentration of ammonia nitrogen in the effluent was generally higher in the control (18-29 mgNH_4^+-N /L) than in the experimental beds (9-24 mgNH_4^+-N/L).

The aeration increased ammonium removal by 69%, 45%, 28%, 18% and 2% for 5, 3, 1.5, 0.5 and 0.2 set points, respectively. As for COD, the difference between the aerated and the non-aerated bed was evident up to and including 0.5 ppm, while no significant differences (2%) were observed at 0.2 ppm.

With regard to nitrites and nitrates, very low concentrations were found in the effluents along the experiment (Table 4). Nitrate concentrations in the experimental wetland clearly showed the effect of the aeration, which was the likely cause for enhanced nitrification and reduced denitrification. Indeed, 6.8±0.1 mgNO_3^--N were found in the effluent of the wetland when continuously aerated. Concentrations decreased to values lower than 0.1 mgNO_3^--N in accordance with the reduction of the dissolved oxygen in the wetland (from 5 to 0.2 mg/L). These results underline that the intermittent aeration of solely a part of the wetland can favor the presence of anoxic conditions enhancing denitrification.

The oxygen consumption rate (OCR) corresponding to 5, 3, 1.5, 0.5 and 0.2 mg/L were 51, 38, 24, 11 and 7g/m^2·d. Significantly lower values (5.7 g/m^2·d) were found for the control. The OCRs for the forced aerated bed were below the range found in literature (50 – 134 g/m^{2}d) (Nivala et al. 2013). This was probably due to the experimental set up, since in this experiment only the 8% of the surface was aerated. Moreover, it should be taken into account that the aeration system was not optimized.

The results presented in this study show that aeration significantly improved the treatment performances. Considering European legislation (91/271/CEE) effluents concentrations of the control were near to the threshold. In general, these systems have higher efficiency, but is has to be considered that the organic loading rate in this experiment was high (40-60 gCOD/m^2·d) compared to the normal values (5 gCOD/m^2·d). Therefore we can assume that the control fulfilled the legislation threshold. In this case, aeration could be seen as a strategy to reduce the surface of the beds without affecting the performances (Kadlec and Wallace, 2009).

Based on the efficiency of aerated beds in comparison with the control the potential reduction of the surface of the beds could be calculated, as shown in Table 5 which indicates the percentage of surface reduction according to the COD and the NH4+-N removal efficiency.

According to the surface reduction for CWs of different sizes and locations, summarized in Table 5, the cost (€/year) of different wetlands size (100, 500 and 1,000 PE) was calculated for two locations (Spain and United Kingdom) (Figure 3).

In general CW costs are higher in United Kingdom. The results showed that every aeration configuration entailed an economic advantage with respect to the control. In the case of a set point at 0.2 mg/L no difference was found between an aerated bed and the control. However, already from an aeration set-point of 0.5 mg/L the electric consumption was largely covered by the surface reduction, reducing the costs by 27-31 % considering COD removal and by 10-14 % considering the ammonium removal. In general up to 50% of the costs could be reduced with the continuous aeration of the beds.

It should be noted that the calculations were performed considering the configuration of this experiment (i.e. aeration of 8% of the total surface). The results highlight that the land and excavation cost has a significant weighting on the total CWs cost, thus the reduction of the surface justifies the aeration of the beds in spite of the increase in the power consumption.

In this study the effect of continuous and intermittent aeration were tested in terms of oxygen supply. Further experimental testing should examine the influence of the proportion of surface aerated and the position of the aeration within a CW.

Heating as a strategy for clogging prevention and remediation

It is well known that the organic matter accumulated within the granular medium is among the main responsible factors for CWs clogging. According to Wang et al. (2014), heating of CW can be a suitable strategy to release the retained organic matter.

During the heating experiment (from March to May), the control water temperature was 13±5 °C, while the water temperature of the experimental wetland was 26±8°C.

As shown in Figure 4, heating the experimental bed at 21°C did not enhance the COD removal. The mean value of COD concentration in the effluent of the experimental and control CWs were 126±37 mg/L and 135±27 mg/L, respectively. The differences between beds were not statistically significant ($p > 0.05$) during the two months of experimentation.

During the first 10 days of experimentation, the COD concentration in the effluent of the experimental wetland was 176±14 mg COD/L, which was 15% higher than the control concentration (153±18 mg COD/L). The authors consider that this could be attributed to the hydrolysis and subsequently release of part of the organic matter retained in the granular medium (Conant et al., 2011), meaning that the heating enhanced by 15% COD mobilization in the experimental wetland.

In order to quantify the benefit of heating the delay on the annual solids accumulation corresponding to the COD mobilization was calculated. Taking into account the correlation factor of 0.84 between VSS and COD (Caselles-Osorio and Garcia, 2007), 0.02 g/L VSS were removed in 1 day of heating.

Considering the VSS/TSS and the solids accumulation rate found in literature the TSS mobilization and the delay on the annual solids accumulation were calculated for the hypothetical heating during 10 days per year on 8% of the surface of the wetland as summarized in Table 3. The TSS removal was calculated for 11 real HSSF CWs (Tanner et al 1998; Caselles-Osorio et al. 2007; Martin et al. 2010). The results highlighted that heating CWs would delay the annual solids accumulation by 8 to 28 days, depending on the VSS/TSS considered. In order to delay the annual solids accumulation for 1 year of operation, it would be necessary to heat 8% of the surface during 200 days (on average). This means that heating 10 days per year during 20 years would delay 1 year of the annual solids accumulation. Considering the electric consumption of heating (7.2 KWh/d), the annual cost for the application of this strategy would be 20 €/m^2·year. According to Nivala et al. (2012), the cost of the gravel excavation and landfill or gravel excavation, washing and reuse is approximately 5 €/m^2.

It should be taken into account that the experiments have been carried out in the Mediterranean region in spring, where the temperatures were rising, with the average water temperature of the control being 18°C). It is therefore possible that the hydrolysation of the organic matter could be enhanced by heating wetlands during the cold season, but this would require further work.

Conclusions

In this study forced aeration and heating were investigated in a pilot plant that constituted of two horizontal flow subsuperficial constructed wetlands treating urban wastewater. Continuous forced aeration increased organic matter (COD) and ammonium nitrogen removal by 56% and 69%, respectively. Improvements in the wastewater treatment were satisfactory for intermittent forced aeration until oxygen concentrations within the wetlands were maintained at 5 mg/L.

Forced aeration can result into reduction of the surface area, leading to significant cost reduction. This study highlighted that the land and excavation cost had a significant weight on the total constructed wetlands cost. Thus, in spite of the increase of the electric consumption, the reduction of the surface could justify the continuous aeration of the beds.

Even if the heating of 8% of the wetland surface at 21°C had no effects on treatment performances, positive effect were noticed on the solids accumulation rate within the granular medium, which is closely related to clogging development. Results demonstrated that heating for 10 days per year during 20 years would delay of 1 year of the annual solids accumulation. Thus, heating of a small area of CWs could be an efficient solution to reduce the annual solids accumulation rate, delaying the clogging of the bed.

This study provided encouraging outcomes for intensive constructed wetlands. Nevertheless, further research is needed in order to reproduce the results using full scale systems over a longer time scale.

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References

APHA-AWWA-WEF, 2005, Standard methods for the examination of water and wastewater. 21st ed. Washington, DC: American Public Health Association.

Bavor H.J. and Schulz, T.J., 1993, Sustainable suspended solids and nutrient removal in large-scale, solid-matrix, constructed wetland systems G.A.Moshiri (Ed.), Constructed Wetlands for Water Quality Improvement, Lewis Publishers, Boca Raton, Florida, pp. 646–656.

Boog J, Nivala J, Aubron T, Wallace S, Afferden M, Müller RA, 2014, Hydraulic characterization and optimization of total nitrogen removal in an aerated vertical subsurface flow treatment wetland. Biores. Technol. 162, 166–174.

Caselles-Osorio A, García J, 2007, Impact of continuous and intermittent feeding strategies on the performance of shallow horizontal subsurface-flow constructed wetlands. Sci. Total Environ 378: 253–62.

Chazarenc F., Gagnon V., Comeau Y., Brisson J., 2009, Effect of plant and artificial aeration on solids accumulation and biological activities in constructed wetlands .Ecol. Eng. 35 (6): 1005–1010.

Conant RT, Ryan MG, Agren GI, Birge HE, Davidson EA, Eliasson PE, 2011, Temperature and soil organic matter decomposition rates — synthesis of current knowledge and a way forward. Glob Chang Biol. 17: 392–404.

Conley L.M., Dick R.I., Lion L.W., 1991, An assessment of the Root Zone Method of wastewater treatment. Journal of the Water Pollution Control Federation, 63 (3): 239 – 247.

Cooper, P.F., 2005, The performance of vertical-flow constructed wetland systems with special reference to the significance of oxygen transfer and hydraulic load-ing rate. Water Sci. Technol. 51 (9): 81–90.

Faulwetter, J.L., Gagnon, V., Sundberg, C., Chazarenc, F., Burr, M.D., Brisson, J., Camper, A.K., Stein, O.R., 2009, Microbial processes influencing performance of treatment wetlands: a review. Ecological Engineering 35: 987–1004.

García J, Aguirre P, Mujeriego R, Huang Y, Ortiz L, Bayona JM., 2004, Initial contaminant removal performance factors in horizontal flow reed beds used for treating urban wastewater.Water Res. 38(7):1669–78.

García, J., Aguirre, P., Barragán, J., Mujeriego, R., Matamoros, V., Bayona, J.M., 2005, Effect of key design parameters on the efficiency of horizontal subsurface flow constructed wetlands: long-term performance pilot study. Ecological Engineering 25:405–418.

García J, Rousseau DPL,Morató J, Lesage E,Matamoros V, Bayona JM., 2010, Contaminant removal processes in subsurface-flow constructed wetlands: a review. Crit Rev Environ SciTechnol 40(7):561–661.

Griffin, L. Wilson, D. Cooper, 2008, Changes in the use, operation and design of sub-surface flow constructed wetlands in a major UK water utility S.K. Billore, P. Dass, J. Vymazal (Eds.), Proceedings of the 11th International Conference on Wetland Systems for Water Pollution Control, 1–7 November 2008, Vikram University and IWA, Indore, India, :419–426

Headley, T., Nivala, J., Kassa, K., Olsson, L., Wallace, S., Brix, H., VanAfferden, M., Muller, R.A., 2013, Escherichia coli removal and internal dynamics in subsurface flow ecotechnologies: effects of design and plants. Ecol. Eng. 61: 564-574.

Hughes-Riley, T., Newton, M.I., Morris, R.H., 2014, Temperature dependence of magnetic resonance sensors for embedding into constructed wetlands, 1st International Electronic Conference on Sensors and Applications, 1-16 June 2014.

Kadlec, R., Wallace, S., 2009. Treatment Wetlands, second ed. CRC Press, Boca Raton, Florida.

Kirschbaum MUF. 2004, Soil respiration under prolonged soil warming: are rate reductions caused by acclimation or substrate loss, Glob Chang Biol 10:1870–7.

Knowles, P., Dotro, G., Nivala, J., García, J., 2011. Clogging insubsurface-flow treatment wetlands: occurrence and contributing factors. Ecological Engineering 37 (2): 99-112.

Martín, I., Salas, J.J., Sardón, N., Pidre, J.R., 2010.Research on clogging and effective surface in subsurface flow constructed wetlands. In: Masi, F., Nivala, J. (Eds.), Proceedings of the 12th International Conference on Wetland Systems for Water Pollution Control, 4e8 October 2010. IRIDRA S.r.l. and IWA, Venice, Italy, 109-115.

Morris, R.H., Newton, M.I., Knowles, P.R., Bencsik, M., Davies, P.A., Griffin, P., McHale, G., 2011. Analysis of clogging in constructed wetlands using magnetic resonance, Analyst, 136, 2283-2286

Nivala, J., Hoos, M.B., Cross, C., Wallace, S., Parkin, G., 2007. Treatment of landfillleachate using an aerated, horizontal subsurface-flow constructed wetland. Sci.Total Environ. 380: 19–27.

Nivala J. , Knowles P., Dotro G., Garcìa J., Wallace S. 2012, Clogging in subsurface-flow treatment wetlands: Measurement, modeling and management, Water Research 46: 1625 - 1640.

Nivala, J., Headley, T., Wallace, S., Bernhard, K., Brix, H., Van Afferden, M., Arno Müller, R., 2013, Comparative analysis of constructed wetlands: The design and construction of the ecotechnology research facility in Langenreichenbach, Germany. EcologicalEngineering 61: 527–543.

Ortega E., Ferrer Medina Y., Salas Rodriguez J.J., Aragon Cruz C., Real Jimenez A., 2010, Manual para la implantacion de sistemas de depuracion en pequenas poblaciones. Ministerio de Medio Ambiente Y Medio Rural Y Marino: 140 – 160.

Pedescoll, A., Corzo, A., Álvarez, E., García, J., Puigagut J., 2011, The effect of primary treatment and flow regime on clogging development in horizontal subsurface flow constructed wetlands: An experimental evaluation. Water Research 45 (12), 3579-3589.

Pedescoll A, Uggetti E, Llorens E, Granés F, García D, García J, 2009, Practical method based on saturated hydraulic conductivity used to assess clogging in subsurface flow constructed wetlands. Ecol. Eng. 35 (8), 1216-1224.

Puigagut J, Villaseñor J, Salas JJ, Bécares E, García J., 2007, Subsurface-flow constructed wetlands in Spain for the sanitation of small communities: a comparative study. Ecol Eng;30: 312–9.

Rousseau D.P.L., Vanrolleghem, P.A., De Pauw, N., 2004, Model-based design of horizontal subsurface flow constructed treatment wetlands: a review. Water Research 38 (6): 1484–1493.

Tanner, C.C., Sukias, J.P.S., Upsdell, M.P., 1998, Organic matter accumulation and maturation of gravel bed constructed wetlands treating dairy farm wastewaters. Water Research 32 (10): 3046 - 3054.

Wallace S. D., Knight R.L., 2006, Small-scale Constructed Wetland Treatment systems: Feasibility, Design Criteria, and O&M Requirements Water Environment Research Foundation (WERF), Alexandria, Virginia.

Wang H., Holden J., Zhang Z., Li M., Li X., 2014, Concentration dynamic and biodegradability of dissolved organic matter in wetland soils subjected to experimental warming, Science of the Total Environment 470–471: 907–916.

Wu S., Kuschk P., Brix H., Vymazal J., Dong R., 2014, Development of constructed wetlands in performance intensification for wastewater treatment: A nitrogen and organic matter target review, Water Research 57: 40-55.

Tables and figures

Table 1. Investment and operation costs of artificially aerated constructed wetlands in Spain and United Kingdom over a 20 year period for 100, 500 and 1,000 PE.

	Costs (€/m^{2}year)		
	100 PE	500 PE	1,000 PE
Spain (according to Ortega et al., 2010)			
Construction	2.6	2.6	2.5
Construction of the aeration system	2.1	3.2	3.3
Operation and maintenance	4.3	2.6	2.3
United Kingdom (according to ARM Ltd. data)			
Construction	4.5	4.2	4.2
Construction of the aeration system	15.9	8.0	6.1
Operation and maintenance	8.3	8.3	8.3

Table 2. Power consumption and cost calculated experimentally for each aeration set point.

Aeration set point (mg/L)	**Working time of the air pump (min/d)**	**Consumption (kWh/m^{2}year)**	**Cost (€/m^2 year)**
5	1440	0.029	14.5
3	626	0.017	8.4
1.5	326	0.008	4.4
0.5	55	0.003	1.5
0.2	23	0.001	0.6

Table 3. Total solids released and delay of the annual solids accumulation assuming heating 8% of the surface during 10 days/year.

VSS/TSS	**Solids accumulation rate (Kg/DM m^{2}year)**	**Solids released (kg TSS /m^2·year)***	**Delay of the annual solids accumulation (d)****	**Reference**
80	1.3	0.04	9	Tanner et al. (1998)
80	1.5	0.04	8	
80	1.9	0.04	6	
80	3.0	0.04	4	
24	2.0	0.12	21	Caselles-Osorio et al.(2007)
50	1.7	0.06	11	
10	4.7	0.30	24	
11	7.9	0.28	11	
17	2.0	0.17	28	
16	3.9	0.18	15	
24	5.1	0.13	8	Martin et al. (2010)

* Calculated using VSS/TSS solids accumulation rate.

** Calculated using VSS/TSS.

Table 4. Nitrites and nitrates concentration detected in the effluents of the control as well as the forced aerated and heated wetlands.

		Nitrites	**Nitrates**
Aeration			
Oxygen concentration set point (mgO$_2$/L)	Control	<0.1	<0.1
	5	1.0 ± 0.5	6.8 ± 0.1
	3	<0.1	2.0 ± 0.6
	1.5	<0.1	0.4 ± 0.2
	0.5	<0.1	<0.1
	0.2	<0.1	<0.1
Heating			
	Control	<0.1	0.5 ± 0.3
	Heated	<0.1	0.2 ± 0.1

Table 5. Percentage of surface reduction according to the COD and the NH_4^+-N removal efficiency for different aeration set points.

Aeration set points (mgO_2/L)	**% of surface reduction according to the COD removal**	**% of surface reduction according to the NH_4^+-N removal**
5	56%	69%
3	46%	45%
1.5	40%	31%
0.5	35%	18%
0.2	3%	5%

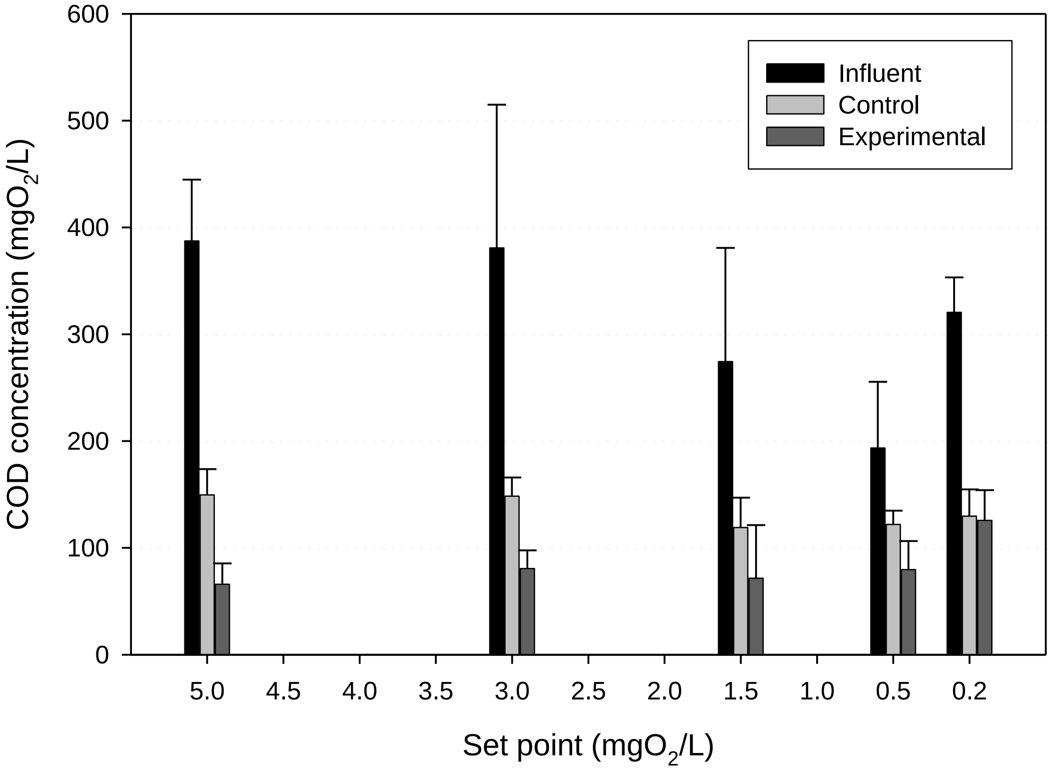

Figure 1. Influent and effluents concentrations of Chemical Oxygen Demand (COD) of control and experimental bed under different operating conditions.

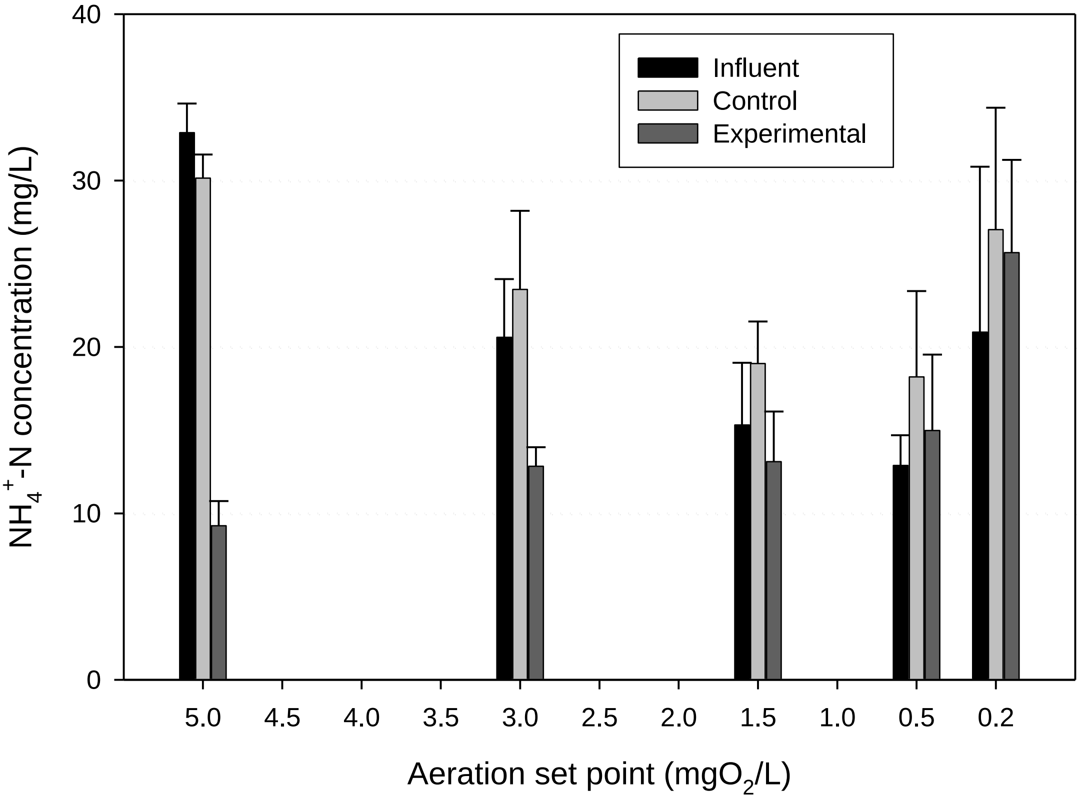

Figure 2. Influent and effluents concentrations of ammonium nitrogen (NH_4^+-N) under different operating conditions.

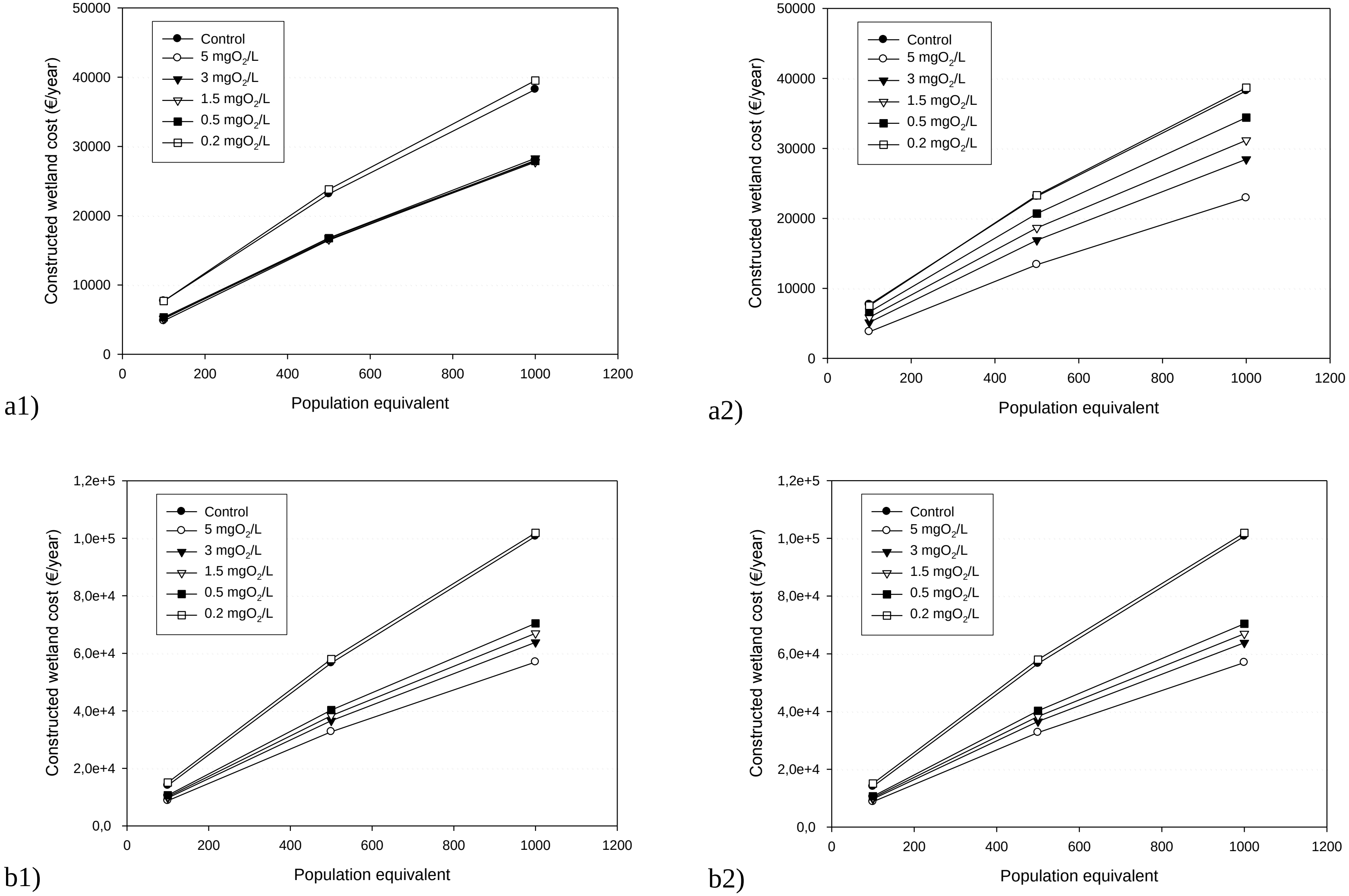

Figure 3. Cost (€/year) of different wetlands size (100, 500 and 1,000 PE) located in Spain (a1, a2) and in United Kingdom (b1, b2)

considering different aeration strategies (set points at 5, 3, 1.5, 0.5, 0.2 mgO_2/L). Data were calculated according to the percentage of surface reduction shown in Table 5. Figures a1 and b1 refers to the surface reduction calculated corresponding to COD removal, while figures a2 and b2 were refers to the surface reduction corresponding to ammonium removal.

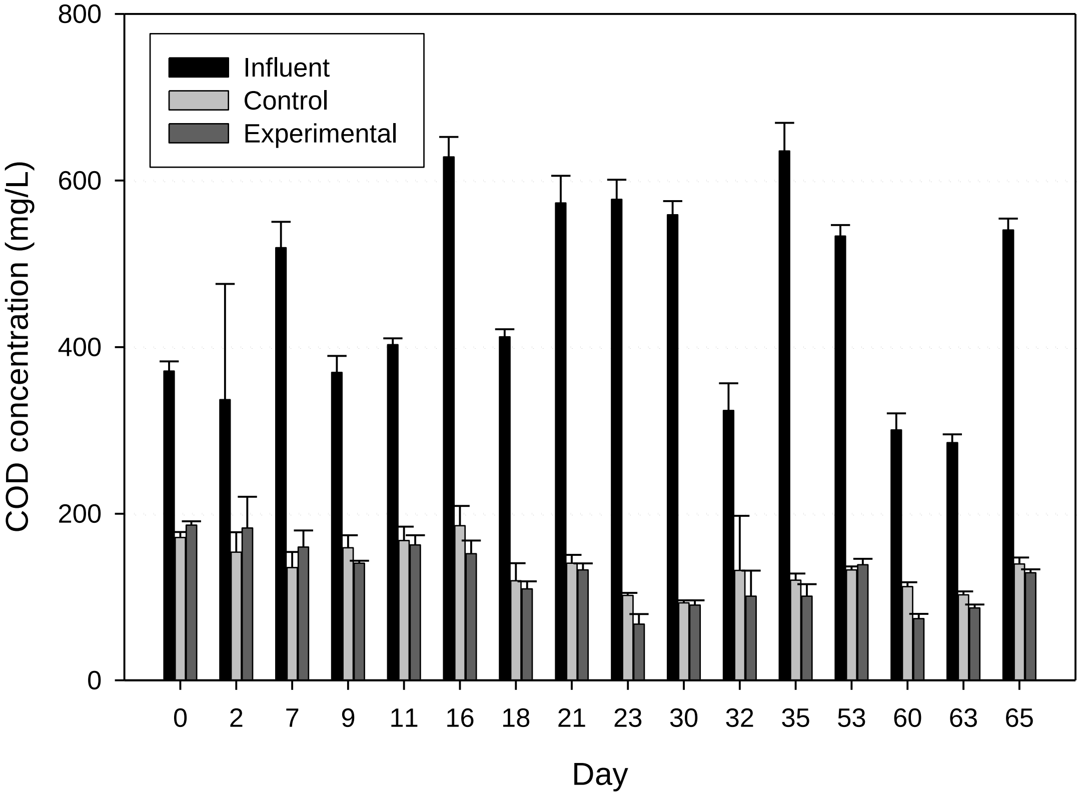

Figure 4. Influent and effluents concentrations of Chemical Oxygen Demand (COD) of control and experimental bed under heating.