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Title: Assessing the economic suitability of aeration and the influence of bed heating on constructed wetlands treatment efficiency and life-span

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Abstract: Constructed wetlands including aeration and heating were studied to improve treatment efficiency and prevent clogging. The experiments were carried out in a pilot plant (0.4 m²) treating urban wastewater with an organic loading rate of 40-60 gCOD/m²·d. Continuous and intermittent aeration was performed from the bottom on 8% of the wetland surface, leading to different dissolved oxygen concentrations within the wetlands (from 0.2 to 5 mgO₂/L). Continuous aeration increased organic matter (COD) and ammonium nitrogen removal by 56% and 69%, respectively. Improvements in wastewater treatment caused by aeration can result in reduction of the surface area requirement of future systems. 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 performance, 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.

Research Highlights

The effect of aeration and heating was tested in a pilot constructed wetland

Continuous aeration increased organic matter and ammonium removal by 56% and 69%

Continuous aeration can result into reduction of the surface area

Electricity costs of continuous aeration was covered by the reduction of the surface

Heating had a positive effect on solids accumulation rate delaying clogging

**Assessing the economic suitability of aeration and the
influence of bed heating on constructed wetlands treatment
efficiency and life-span**

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25   **Abstract**

26

27   Constructed wetlands including aeration and heating were studied to improve treatment
28   efficiency and prevent clogging. The experiments were carried out in a pilot plant (0.4
29   m²) treating urban wastewater with an organic loading rate of 40-60 gCOD/m²·d.
30   Continuous and intermittent aeration was performed from the bottom on 8% of the
31   wetland surface, leading to different dissolved oxygen concentrations within the
32   wetlands (from 0.2 to 5 mgO₂/L). Continuous aeration increased organic matter (COD)
33   and ammonium nitrogen removal by 56% and 69%, respectively. Improvements in
34   wastewater treatment caused by aeration can result in reduction of the surface area
35   requirement of future systems. This work demonstrated that for the studied
36   configuration the cost of the power consumption of the continuous aeration was largely
37   covered by the reduction of the wetlands surface. Even if the heating of 8% of the
38   wetland surface at 21°C had no effects on treatment performance, positive results
39   showed that solids accumulation rate within the granular medium, which is closely
40   related to the development of clogging. It has been demonstrated that heating for 10
41   days per year during 20 year period would delay the equivalent of 1 year of solids
42   accumulation.

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

45

46   **Introduction**

47   Constructed wetlands (CW) are widely used for the treatment of wastewater including
48   urban wastewater, mine water, landfill leachate, industrial effluents, air-striprunoff and
49   road runoff (Kadlec and Wallace, 2009).

50   In horizontal subsurface flow constructed wetlands (HSSF CW) the water, maintained
51   at a constant depth, flows horizontally below the surface of a granular medium planted
52   with emergent rooted wetland vegetation. In such systems contaminants are removed
53   through a number of physical, chemical, and biological processes taking place
54   simultaneously (García et al., 2010). Note that vertical flow constructed wetlands, are
55   not a topic covered in this manuscript.

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

59   Since HSSF CWs are generally considered to be anaerobic, organic matter oxidation
60   and nitrification may be enhanced by promoting more oxidized conditions (Caselles-
61   Osorio and García 2007). Among the strategies to increase CW performance, forced (or
62   active) aeration patented by Wallace (2001) has been recently suggested as an efficient
63   way to improve removal of organic matter and reduced nitrogen species (Nivala et al.
64   2007; Wu et al. 2014; Fan et al., 2013a).

65   Since the year 2000, active aerated systems have shown interesting results increasing
66   significantly the removal rates compared to passive systems (Ouellet-Plamondon et al.
67   2006; Maltais-Landry et al. 2009). A laboratory-scale study has indicated that aeration
68   has a certain effect on the solids degradation rates, increasing the amount of
69   accumulated total organic suspended solids against the mineral fraction (Chazarenc et
70   al., 2009; Zhang et al., 2010).

71 In spite of the advantages of aeration, the costs increase should be taken into account as
72 CW ordinarily have a low operating cost. Most of the studies on active aeration referred
73 to “continuous aeration mode”(i.e. 24 h per day) which has a significant energy
74 consumption. Nonetheless, energy requirements of aerated CW ($0.16\text{--}0.49\text{ kWh/m}^3$ of
75 water treated) are still largely lower than conventional wastewater treatments such as
76 activated sludge ($0.76\text{--}0.88\text{ kWh/m}^3$ treated) (Kadlec and Wallace, 2009; Austin and
77 Nivala, 2009).

78 Moreover, this option can lead to a contradiction between the removal of ammonium
79 and total nitrogen because of the lack of favourable anoxic conditions for denitrification
80 (Wu et al., 2014). Important improvements could be achieved with intermittent aeration
81 where the level of aeration could be adjusting and controlled (i.e. adjusting the
82 dissolved oxygen within the wetland) and excessive aeration could be avoided (Fan et
83 al., 2013b). In this case intermittent aeration has been shown to achieve high total
84 nitrogen removal by providing alternate aerobic/anoxic conditions for the
85 simultaneously occurring nitrification and denitrification (Boog et al., 2014; Li et al.,
86 2014).

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

91 Apart from the efficiency in pollutant removal, the clogging of the porous medium is
92 among the main operational problems of HSSF CW. Clogging may result in hydraulic
93 malfunction associated with reduced treatment performance due to preferential water
94 flows, dead zones and short circuits. Clogging affects the longevity of the systems,
95 indeed the original life span predictions were in the order of 50–100 years (Conley et

96 al., 1991) whereas experimental evidence has shown lifetimes of 8 years (Griffin et al.,
97 2008).

98 Clogging has been widely studied during recent years (Knowles et al., 2011; Nivala et
99 al., 2012; Maloszewski et al., 2006; Murphy et al., 2010; Ragusa et al., 2004; Tietz et
100 al., 2007). It is well known that clogging is caused by the accumulation of materials
101 associated with treatment. The quantity and composition of the clog matter may vary
102 but typically consists of highly hydrated gels and sludge with inorganic (e. g. solids
103 from chemical erosion of gravel) and organic solids (e.g. biomass growth, plant roots,
104 biofilm and plant detritus)(Knowles et al., 2011; Pedescoll et al., 2011a).

105 It is generally accepted that soluble COD in spring or beginning of summer increases at
106 the outlet of a wetland, thus decreasing treatment efficiency after winter time (Pedescoll
107 et al., 2011b). This is mainly due to the organics accumulation during winter. When
108 temperature raises (spring time) hydrolysis of organics retained in the wetlands
109 increases. The increase of the temperature within the CW may enhance the organic
110 matter oxidation (Garfi et al., 2012; Kirschbaum et al., 2004). In this context, warming
111 up the wetland might be of use not only on the increase of treatment efficiency but also
112 on the mobilization of organics accumulated within the treatment bed. Furthermore,
113 nitrification is limited in winter time (even in warm regions such as Spain). Warming
114 the water up few degrees at the beginning of spring-time could help to decrease the
115 soluble background COD generally found in this period. Increased background COD at
116 the beginning of spring is a consequence of organics hydrolysis accumulated during
117 winter time.

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

121 **Materials and Methods**

122 *Pilot plant*

123 The experimental plant was located in Barcelona (Spain) at the Department of
124 Hydraulic, Maritime and Environmental Engineering of the Universitat Politècnica de
125 Catalunya·BarcelonaTech. The plant was set in operation in March 2011. Wastewater
126 was pumped from a municipal sewer where it was then screened and subsequently
127 stored for approximately 5 h in a continuously stirred plastic tank (1.2 m³ volume). The
128 primary treatment consisted of a hydrolytic upflow sludge bed reactor (HUSB) with 3 h
129 of hydraulic retention time (HRT). The primary treatment was followed by two HSSF
130 CW in parallel acting as secondary treatment. Each CW was made of a PVC container
131 with a surface of 0.4 m² (0.75 m long, 0.55 m wide, 0.39 m high). A uniform gravel layer
132 (40% initial porosity) was used which provided a wetland depth of 0.35 m. The water
133 level was kept at 0.05 m below the gravel surface to give a water depth of 0.30 m, as
134 suggested by García et al. (2004). CW were planted with common reed
135 (*Phragmites australis*) at an initial density of 16 plants/m².

136 Both CW were fed under continuous flow regime and operated at 0.8 days HRT,
137 hydraulic loading rate (HLR) of about 160 L/m²·d and an organic loading rate (OLR)
138 ranging from 40 to 60 gCOD/m²·d. Such conditions were set in order to “force” the
139 systems to detect the effect of aeration and heating.

140 In order to measure the evapotranspiration, the water flow was measured at the inlet and
141 at the outlet of each wetland by means of peristaltic pumps (at the inlet) and a flow
142 meter device located at the outlet. However, values recorded from the flow meter device
143 indicated that evapotranspiration effect was negligible during the experimental period.

144

145 *Physical and Chemical analysis*

146 Water quality was monitored from influent and effluents samples twice a week from
147 November 2013 to May 2014. The surveyed water quality parameters were the total
148 chemical oxygen demand (COD), ammonia nitrogen, nitrite and nitrate nitrogen. Such
149 parameters have been selected as reliable indicators for water quality monitoring.
150 Analyses were carried out according to Standard Methods (APHA-AWWA-WEF,
151 2005). Nitrite and nitrate nitrogen was analyzed with ion chromatograph (ICS1000,
152 Dionex, USA).

153 *Aeration experiment*

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

158 The aeration system consisted of a pierced resin pipe of about 50 cm long, rolled at the
159 bottom of the wetland at its central zone (Figure 1). The aeration roll occupied a surface
160 of 0.03 m², which corresponded to 8% of the total bed surface. The air was injected by
161 means of an air pump working at a flow rate of 720 L/h.

162 Dissolved oxygen at the bottom of both of the CW was continuously monitored by
163 means of a dissolved oxygen probe placed above the aeration device (CS512 Oxyguard
164 Type III, Campbell Scientific Inc., USA) connected to a data logger (CR1000,
165 Campbell Scientific Inc., USA).

166 At the beginning of the experiment air was continuously injected (24h/d), reaching an
167 oxygen concentration within the bulk liquid of 5 mg/L. Afterwards, in order to have an
168 intermittent aeration, the oxygen concentration within the bed was controlled by means
169 of a control program of the data logger (control Deadbond version 2.5). This program
170 worked according to oxygen concentration set points. The valve controlling air injection

171 was opened when the oxygen concentration was higher than the set point and airflow
172 stopped when the set point concentration was reached. Thus, after 9 days of continuous
173 aeration the oxygen concentration within the bed was set at 3 mg/L and successively
174 reduced to 1.5, 0.5 and 0.2 mg/L in order to test the treatment performance at different
175 aeration rates. Each condition was maintained during 2 weeks. The aeration
176 configuration and the control system were able to constantly provide the pre-established
177 oxygen concentrations within the bed.

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

$$180 \quad \text{Removal efficiency}(\%) = \left(1 - \frac{C_e}{C_i}\right) * 100 \quad \text{Eq. 1}$$

181 Where C_e was the effluent concentration (in mg/L) and C_i was the influent
182 concentration. The statistical significance of the experimental results was evaluated by
183 the repeated measures ANOVA test using R statistics software.

184 Data was used to compare the cost of the aeration in each configuration in order to
185 assess the viability of the active aeration (Table 1). Three wetlands sizes were
186 considered for this study, corresponding to 100, 500 and 1,000 (PE). These sizes were
187 selected as a range of small-medium communities. This study was carried out
188 considering a wetland located in Spain and a wetland located in the United Kingdom.

189 For each CW, the annual cost was calculated including construction and maintenance
190 considering a 20 year amortization period. The costs of the Spanish CW were calculated
191 using information provided by Ortega et al. (2010), while data for the CW costs in
192 United Kingdom were provided by ARM Ltd (Rugeley, UK). Both cases were
193 calculated considering the price in euro for the year 2010. The electric consumption
194 (Table 2) was calculated according to data gathered from the experiments carried out in
195 the pilot plant.

196

197 *Heating experiment*

198 Even if in Mediterranean countries water temperature in winter might not be a big
199 problem when compared to other countries, nitrification can be highly affected in winter
200 time even in warm regions such as Spain (Pedescoll et al., 2011b). For this reason this
201 experiment was carried out to assess whether warming up the water few degrees at the
202 beginning of spring-time would be of use not only to rise the nitrification but also to
203 reduce background COD coming from winter accumulation of organics. In order to test
204 the effect of temperature on CW, from March to May 2014, a heating system (Wave
205 300W) was introduced into the center of the experimental wetland, with a temperature
206 set to 21°C. As for aeration, the removal efficiency of the experimental wetlands was
207 calculated with respect to the control wetland for COD (Eq. 1).

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

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

220   **Results and discussion**

221   *Aeration as a strategy to increase treatment efficiency*

222   The aeration at different set points entailed significant increment of dissolved oxygen
223   within the wetland, and a consequent increase in COD and $\text{NH}_4^+\text{-N}$ removal
224   ($p<0.05$). This means that, even if the aeration was not uniformly distributed along the
225   surface area, the aeration was efficient. As shown in Figure 2, for a COD concentration
226   of 311 ± 80 mgO_2/L in the inlet a decrease to 134 ± 14 mgO_2/L at the outlet was observed
227   in the control bed, whereas lower values (about $70\text{mgO}_2/\text{L}$) were reached in the effluent
228   of the beds with oxygen concentration set at 5, 3, 1.5 and 0.5 mg/L . No significant
229   differences ($p>0.05$) were found between the effluents concentrations of the
230   experimental beds. Conversely, the COD concentrations in the effluent of the control
231   and the experimental beds were similar when the aeration set point was 0.2 mg/L . The
232   differences between the COD concentration in the effluents of the two beds decreased
233   from 80 to 40 mg/L when the aeration set point was 0.5 mg/L , while almost no
234   differences between the systems was observed when the set point was 0.2 mg/L was set
235   as the aeration set point. On the whole, aeration increased COD removal by 56%, 46%,
236   40%, 35% and 3% for 5, 3, 1.5, 0.5 and 0.2 set points, respectively.

237   Concerning ammonium nitrogen ($\text{NH}_4^+\text{-N}$) (Figure3), differences between systems with
238   and without aeration were even more evident. Ammonia nitrogen concentrations in the
239   influent ranged between 14 and 32 $\text{mgNH}_4^+\text{-N/L}$ due to variations in the wastewater
240   quality. The concentration of ammonia nitrogen in the effluent was generally higher in
241   the control ($18\text{-}29$ $\text{mgNH}_4^+\text{-N/L}$) than in the experimental beds ($9\text{-}24$ $\text{mgNH}_4^+\text{-N/L}$).
242   Note that in some cases the effluents concentrations was higher than the influent, this
243   could be partially due to ammonification and to the fact that the influent values do not
244   correspond to the effluent of the same day (due to the HRT).

245 The aeration increased ammonium removal between the control and the experimental
246 wetland by 69%, 45%, 28%, 18% and 2% for 5, 3, 1.5, 0.5 and 0.2 set points,
247 respectively. As for COD, the difference between the aerated and the non-aerated bed
248 was evident up to and including 0.5 ppm, while no significant differences (2%) were
249 observed at 0.2 ppm ($p > 0.05$).

250 With regard to nitrites and nitrates, very low concentrations were found in the effluents
251 along the experiment (Table 4). Nitrate concentrations in the experimental wetland
252 clearly showed the effect of the aeration, which was the likely cause for enhanced
253 nitrification. Moreover, the higher the oxygen supply to the wetland reduced the anoxic
254 environment for denitrification to take place.

255 Indeed, $6.8 \pm 0.1 \text{ mgNO}_3^- \text{-N}$ were found in the effluent of the wetland when continuously
256 aerated. Concentrations decreased to values lower than $0.1 \text{ mgNO}_3^- \text{-N}$ in accordance
257 with the reduction of the dissolved oxygen in the wetland (from 5 to 0.2 mg/L). These
258 results underline that the intermittent aeration of solely a part of the wetland can favor
259 the presence of anoxic conditions enhancing denitrification.

260 The results presented in this study show that aeration significantly improved the
261 treatment performance. Considering European legislation (91/271/CEE) effluent
262 concentrations of the control (119-149 mg/L) were near to the threshold (125 mg/L).
263 Therefore we can assume that the control fulfilled the legislation threshold. In this case,
264 aeration could be seen as a strategy to reduce the surface of the future beds without
265 affecting the performance (Kadlec and Wallace, 2009).

266 Based on the efficiency of aerated beds in comparison with the control the potential
267 reduction of the surface of the beds could be calculated, as shown in Table 5 which
268 indicates the percentage of surface reduction according to the COD and the $\text{NH}_4^+ \text{-N}$
269 removal efficiency.

270 According to the surface reduction for CW of different sizes and locations, summarized
271 in Table 5, the cost (€/year) of different wetlands size (100, 500 and 1,000 PE) was
272 calculated for two locations (Spain and United Kingdom) (Figure 4). An average soil
273 cost was used for each country.

274 In general CW costs are higher in United Kingdom. The results showed that every
275 aeration configuration entailed an economic advantage with respect to the control. In the
276 case of a set point at 0.2 mg/L no difference was found between an aerated bed and the
277 control. However, already from an aeration set-point of 0.5 mg/L the electric
278 consumption was largely covered by the surface reduction, reducing the costs by 27-
279 31% considering COD removal and by 10-14% considering the ammonium removal. In
280 general up to 50% of the costs could be reduced with the continuous aeration of the
281 beds.

282 It should be noted that the calculations were performed considering the configuration of
283 this experiment (i.e. aeration of 8% of the total surface). Hydraulic aspects have not been
284 considered in this study, in fact it should be verified if the decrease of HRT due to the
285 reduction of surface area could affect the treatment efficiency.

286 The results highlight that the land and excavation cost has a significant weighting on the
287 total CW cost, thus the reduction of the surface justifies the aeration of the beds in spite
288 of the increase in the power consumption. It is important to take into account that results
289 are based on theoretical calculations and more data at different size are required to
290 confirm these findings.

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

294

295 *Heating as a strategy for clogging prevention and remediation*

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

299 During the heating experiment (from March to May), the control water temperature was
300 13 ± 5 °C, while the water temperature of the experimental wetland was 26 ± 8 °C.

301 As shown in Figure 5, heating the experimental bed at 21°C did not enhance the COD
302 removal. The mean value of COD concentration in the effluent of the experimental and
303 control CW were 126 ± 37 mg/L and 135 ± 27 mg/L, respectively. The differences between
304 beds were not statistically significant ($p > 0.05$) during the two months of
305 experimentation.

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

312 In order to quantify the benefit of heating the delay on the annual solids accumulation
313 corresponding to the COD mobilization was calculated. Taking into account the
314 correlation factor of 0.84 between VSS and COD (Caselles-Osorio and Garcia, 2007),
315 0.02 g/L VSS were removed in 1 day of heating.

316 Considering the VSS/TSS and the solids accumulation rate found in literature the TSS
317 mobilization and the delay on the annual solids accumulation were calculated for the
318 hypothetical heating during 10 days per year on 8% of the surface of the wetland as
319 summarized in Table 3. The TSS removal was calculated for 11 real HSSF CW (Tanner

et al 1998; Caselles-Osorio et al. 2007; Martin et al. 2010). The results highlighted that heating CW 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€/m²·year. According to Nivala et al. (2012), the cost of the gravel excavation and landfill or gravel excavation, washing and reuse is approximately 5€/m². 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 hydrolysis of the organic matter could be enhanced by heating wetlands during the cold season, but this would require further work.

Conclusions

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

344 increase of the electric consumption, the reduction of the surface could justify the
345 continuous aeration of the beds.

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

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

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479 **Tables and figures**

480

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 (€/m²year)		
	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

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Table 2. Powerconsumption andcost calculated experimentally for each aeration set point.

Aeration set point (mg/L)	Working time of the air pump (min/d)	Consumption (kWh/m² year)	Cost (€/m² 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

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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 m²year)	Solids released (kg TSS /m²·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.

489

Table 4. Nitrites and nitrates concentration detected in the effluents of the control as well as the 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

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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 (mgO₂/L)	% of surface reduction according to the COD removal	% of surface reduction according to the NH₄⁺-N removal
5	56%	69%
3	46%	45%
1.5	40%	31%
0.5	35%	18%
0.2	3%	5%

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497 Figure 1. Scheme of the pilot wetland with the aeration systems. During the construction
 498 of the system, a cylindrical part of the central zone of the bed was kept without gravel in
 499 order to allow experiments.

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503 Figure2.Influent and effluents concentrations of Chemical Oxygen Demand (COD) of
504 control and experimental bed under different operating conditions.

505

506 Figure 3. Influent and effluents concentrations of ammonium nitrogen ($\text{NH}_4^+\text{-N}$) under

507 different operating conditions.

Figure 4. 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 mgO₂/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.

508

509 Figure 5. Influent and effluents concentrations of Chemical Oxygen Demand (COD) of
 510 control and experimental bed under heating.

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Supplementary Material

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