Using one filter stage of unsaturated/saturated vertical flow filters for nitrogen removal and footprint reduction of constructed wetlands

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ABSTRACT

French vertical flow constructed wetlands (VFCW) treating raw wastewater have been developed successfully over the last 30 years. Nevertheless, the two-stage VFCWs require a total filtration area of 2–2.5 m²/P.E. Therefore, implementing a one-stage system in which treatment performances reach standard requirements is of interest. Biho-Filter® is one of the solutions developed in France by Epur Nature. Biho-Filter® is a vertical flow system with an unsaturated layer at the top and a saturated layer at the bottom. The aim of this study was to assess this new configuration and to optimize its design and operating conditions. The hydraulic functioning and pollutant removal efficiency of three different Biho-Filter® plants commissioned between 2011 and 2012 were studied. Outlet concentrations of the most efficient Biho-Filter® configuration are 70 mg/L, 15 mg/L, 15 mg/L and 25 mg/L for chemical oxygen demand (COD), 5-day biological oxygen demand (BOD₅), total suspended solids (TSS) and total Kjeldahl nitrogen (TKN), respectively. Up to 60% of total nitrogen is removed. Nitrification efficiency is mainly influenced by the height of the unsaturated zone and the recirculation rate. The optimum recirculation rate was found to be 100%. Denitrification in the saturated zone works at best with an influent COD/NO₃-N ratio at the inlet of this zone larger than 2 and a hydraulic retention time longer than 0.75 days.

Key words: footprint, performance, unsaturated/saturated conditions, vertical flow constructed wetland

INTRODUCTION

The standard French constructed wetland design for raw wastewater treatment consists of a first stage of three alternately loaded gravel-filled vertical flow constructed wetland (VFCW) and a second stage of two sand-filled VFCW. The design and performances of such systems are well known (Troesch & Esser 2012; Morvannou et al. 2015) and enable high levels of nitrification (>85%). They accept relatively high hydraulic loads (Molle et al. 2006; Arias et al. 2014) and they cope with seasonal load variations as well. However, this standard design requires 2–2.5 m² of filter per population equivalent (P.E.), resulting in a total footprint of 3–5 m²/P.E. In addition, the suitable material (sand) for filters of the second stage is not always available. Thus, the standard French design is not always economically competitive. Moreover, low total nitrogen (TN) removal is observed since these systems are aerobic.

Recent works investigated ways to both decrease system footprint and improve ammonia and TN removal. Prost-Boucle & Molle (2012) studied the potential of a one single-stage recirculating wetland. They showed that the nitrification efficiency increases with both effluent recirculation (up to a recirculation rate of 100%) and filter’s surface area increase (up to 1.5 m²/P.E.), but the minimal total Kjeldahl nitrogen (TKN) concentration that can be guaranteed at the outlet is 30 mg/L. On the other hand, a deep single-stage vertical flow bed that combines the two stages into one (Bi-filtre®) aiming at reducing the footprint (1.5 m²/P.E. instead of 2 m²/P.E. for the classical French system) was developed (Troesch et al. 2010). However, it does not guarantee the same removal performances for TKN (20 mg/L and 11 mg/L on average for the Bi-filtre® and the classical French system outlet, respectively). More recently, a design with both unsaturated and saturated...
zones operated with or without recirculation (Prigent et al. 2013; Foladori et al. 2014; Silveira et al. 2015) has been tested. Prigent et al. (2013) suggested the following design: (i) sizing of 1.8 m²/P.E., (ii) 65 cm depth unsaturated zone above a 40 cm depth saturated zone, (iii) recirculation rate of 100%, and (iv) total hydraulic loading rate of 0.48 m/d. Using this design, the outlet average concentrations did not exceed 125 mg chemical oxygen demand (COD)/L, 25 mg biological oxygen demand measured during 5 days (BOD₅)/L, 35 mg total suspended solids (TSS)/L, 20 mg TKN/L and 50 mg TN/L. Prigent et al. (2013) stressed that the surface should not be less than 1.5 m²/P.E. to secure sufficient nitrification, while Foladori et al. (2014) gave a value of 1.3 m²/P.E. In the Foladori et al. (2014) study, the TKN removal efficiency was comprised between 72–87% but decreased to 50% when the system was overloaded. Silveira et al. (2015) tested two different saturated zone depths without recirculation to evaluate the TN removal and the influence of saturation level on the system performance. They observed higher TN removals when the height of the saturated zone increased. However, a supplementary treatment stage is necessary to achieve complete TN removal.

The Biho-Filter® design by Epur Nature combines an unsaturated zone over a saturated zone (Figure 1). Different depths of the unsaturated and saturated zones were tested (see Table 1). The unsaturated upper part is mainly designed following French design guidelines (Molle et al. 2005) given for the first stage VFCW (‘French system’). It ensures the filtration of suspended solids and an aerobic treatment of the dissolved pollution. The saturated lower part filled with coarse gravel allows denitrification and concomitant organic carbon removal. It also retains TSS (mainly detached biofilm). At the interface between the unsaturated and saturated zone aeration pipes allow oxygen transfer to the bottom part of the unsaturated zone (Molle et al. 2008).

The main objective of this study was to assess the potential of this new configuration to optimize its design and operating conditions (bottom saturation layer depth, recirculation rate, etc.). Therefore, the purposes were: (i) to evaluate treatment performances in terms of COD, BOD₅, TSS and nitrogen; (ii) to observe and characterize its hydraulic behaviour; and (iii) to estimate top organic and hydraulic loads that can be dosed without exceeding outlet regulatory concentrations.

On the other hand, the role and the effectiveness of the saturated zone were questioned focusing on the influence of COD/NO₃-N ratio in the saturated zone influent on denitrification, the risk of clogging, and the development of possible anaerobic conditions that can be detrimental to global removal performances of the Biho-Filter® system.

Thus, three full-scale Biho-Filter® plants with different setups (layer depths and recirculation rates) were monitored over 2 years. An advanced monitoring was carried out on one of these three full-scale Biho-Filter® plants including tracer experiments and NH₄-N and NO₃-N online measurements in order to deepen the understanding of the system behaviour.

**MATERIALS AND METHODS**

**Full-scale Biho-Filter® plants: design and characteristics**

Three different full-scale Biho-Filter® plants fed with raw domestic wastewater were monitored. Operating conditions...
varied in order to test the impact of organic and hydraulic loads, recirculation rates, saturation levels and filtration depths. Each plant capacity, design parameters, filter configuration and recirculation rates are summarized in Table 1. The plant no. 1 was built under the Mediterranean climate whereas the plants no. 2 and no. 3 were built under the oceanic one. As this design was still at an experimental level, it was decided to oversize the filters’ surface to ensure that the treatment performances are reached. However, the filters follow the classic 3.5 d feeding/7 d rest operation.

The impact of the recirculation rate on removal efficiencies was mainly studied on plant no. 3 where four recirculation rates were tested (0%, 50%, 100% and 300%). Treatment efficiencies were assessed by 24 h-flow proportional composite samples with refrigerated samplers. TSS, COD, BOD₅, TKN, NH₄-N, NO₃-N were analysed according to Standard Methods (APHA 2012).

**Advanced monitoring**

Plant no. 1 was studied into more details during a 3.5-d monitoring campaign that matches the feeding period of one of the three filters in June 2014.

**Hydraulic monitoring**

Inflow rate was measured by recording (pre-calibrated) pump functioning time. Pumping volume was measured beforehand. Outflow rate was continuously recorded with an ultrasonic sensor on a Parshall flume. Recirculation was set to zero.

In order to estimate the hydraulic behaviour of the filter, two tracer tests (Kadlec & Wallace 2009) were performed during another feeding period (3.5 d) with a time interval of one year. Fluorescein (1.5 mg/L) was injected during the first batch of the feeding period. A fluorimeter analyser (GGUN-FL device) was placed at the outlet of the filter.

**Physical-chemical/gas analyses**

In addition to the 24 h composite samples, redox potential measurements (SEKO-Control SS500) were carried out within the saturated layer by means of piezometers and NH₄-N and NO₃-N concentrations (WTW–Ise probe) were continuously measured at the outlet of the filter. Gaseous oxygen content measurements were carried out in the unsaturated layer by a gas analyzer (Dräger Sensor XS©). Results are expressed in percent of the air phase (O₂ saturation in air being 21%), to within ±0.2%.

All probes and flow monitoring devices were recorded on a data logger at a 1 min time step.

**Saturated zone clogging assessment**

Two high flow discharges of the saturated layer were performed after 1.5 years and 3.5 years of operation on one
filter of the plant no. 1 in order to remobilize TSS accumulated in the saturated zone since the plant commissioning and to estimate their amount. It consisted in opening the valve maintaining the water level in the saturated layer. The outflow was sampled time-regularly in order to assess the quantity of solids (TSS and volatile suspended solids, VSS) which were washed out. All outgoing water was recirculated. The filter was equipped with piezometers connected to the bottom saturated layer. They were used to sample accumulated solids in their vicinities. Measurements were carried out before draining and after reloading to ensure that solids were effectively washed out.

RESULTS AND DISCUSSION

Hydraulic of the filter

Tracer test results

Figure 2 presents the instant tracer concentration and cumulative tracer mass recovery at the outlet of the plant no. 1 during a feeding period of 3.5 d for the second tracer test. The results of both tracer tests carried out at one year apart were substantially similar. About 86% of the tracer mass was recovered. The tracer loss is probably due to light degradation when influent ponds over the surface before infiltrating, and adsorption onto the organic matter and/or the media. Nevertheless, such a recovery rate is still acceptable for a hydraulic description of the system.

The first small outlet tracer peak (less than 1% in mass of tracer) reveals a negligible short cut of the system and the presence of preferential flow. Moreover, several peaks were observed in the next batches. Indeed, even if the tracer is mixed only once with the incoming wastewater, it seems like the tracer application was carried out in several times (remaining tracer in the sump and on filter surface). This phenomenon should come from a heterogeneous water distribution onto the filter surface during the first batches, which were observed during the monitoring and the presence of macropores in saturated and unsaturated layers (Morvannou et al. 2013). During the first feeding batches after a rest period, as the sludge layer is not yet developed on this filter, the water does not reach the entire filter surface but only areas closer to the feeding points (where the sludge layer is most developed). As a consequence, the water and the tracer rapidly flows through the filter.

The hydraulic retention time (HRT) calculated from the tracer test results is 1.1 d (Kadlec & Wallace 2003). On the other hand, considering a water level saturation of 0.6 m and a porosity of 35%, the theoretical estimated HRT is 0.91 d for the saturated layer (assuming a plug flow). This HRT may be overestimated because of preferential flows and dead zones that may result from the particular network of drains this Biho-Filter® (very low drain density according to the filter surface). Thus, the HRT in the unsaturated top layer (0.4 m depth) can be estimated to be around 0.2 d (4.8 h). This is consistent with previous studies done on this kind of filter (Molle 2003). According to Prigent et al. (2013), the height of the saturated layer should be chosen so as to provide an HRT greater than 0.4 d to ensure a good denitrification.

Figure 2 | Tracer (fluorescein) concentration measured at the outlet of the filter over time and cumulative percentage of the recovered tracer mass.
Removal performances

Average removal efficiencies and concentration values measured on each plant are summarized in Table 2. For all plants, applied organic loads are lower than the nominal value of 300 gCOD/m²/d on the filter in operation, as recommended for the French design (Molle et al. 2005). Inlet concentrations of plant no. 3 are lower than those measured in domestic wastewater of French rural areas (<2,000 P.E.) (Mercoiret et al. 2010). This is due to a large clear water intrusion into the sewer.

Globally, removal performances of the Biho-Filter® plants studied are better (93%, 98% and 82% for COD, TSS and TKN removal, respectively) than those of a classical first stage (77%, 83% and 59% for COD, TSS and TKN removal, respectively; Morvannou et al. 2015). As showed by Silveira et al. (2015), higher TSS removal efficiency results from a better entrapment of TSS in the saturated zone. Furthermore, denitrification occurring in the saturated zone not only increases TN removal but also participates to COD consumption.

Suspended solids

The saturated zone may increase the entrapment of solids due to a lower fluid velocity within the pores. High TSS removal efficiency (above 90%) is observed on all plants whatever the organic load and the recirculation rate. As well, Prost-Boucle & Molle (2012), Foladori et al. (2014) and Millot et al. (2016) observed that when the hydraulic and organic loads increased the TSS removal efficiency was not significantly affected.

COD and BOD5

High and stable removal efficiency is observed for COD and BOD5 for all configurations (93% ± 3% and 97% ± 2% for COD and BOD5, respectively) and higher than the ones measured at the outlet of a two-stage French VFCW (87 ± 2% for COD, Morvannou et al. 2015). COD and BOD5 removal efficiency does not exhibit seasonal trends in the unsaturated zone as shown by Prost-Boucle & Molle (2012), Prost-Boucle et al. (2015) and Silveira et al. (2015). In addition to the effect on solids removal, the additional HRT in the saturated zone permits dissolved carbon removal by denitrification. It explains why low outlet concentrations are observed. Prigent et al. (2013) and Millot et al. (2014) observed also this additional COD removal in the saturated layer as well as the increase in COD removal when the saturated zone depth increases. Slow flow in the saturated zone enhances contact time between the denitrifying microorganisms and substrates, which is necessary for good denitrification (NO3-N and COD) (Langengraber et al. 2009; Maltais-Landry et al. 2009; Foladori et al. 2014).

Nitrification

Nitrification, which occurs mainly in the aerobic upper part of the filter (O2 content into the filter ranged between 13.0% and 20.9%), shows removal efficiency comparable to classical systems without a saturated zone (Molle et al. 2008; Prost-Boucle & Molle 2012) with similar filtration depths or recirculation rates. The evolution of inlet TKN and ammonium concentrations (24 h composite samples) as well as ammonium and nitrate concentrations over time at the outlet of the filter observed on plant no. 1 (Figure 3) clearly points out (i) a stable nitrification rate close to 45% during the feeding period, (ii) no nitrate release during the first 0.9 d which is the theoretical HRT of the saturated zone, (iii) followed by a constant denitrification with a maximum nitrate concentration of 4 mg/L in the outflow. While high peaks of nitrate concentrations are commonly measured in the first batches at the outlet of a traditional French first stage of VFCW, the absence of nitrate release with this system is explained by denitrification in the saturated zone during the previous rest period.

For the plant no. 5 with similar operating conditions (hydraulic load, TKN load, recirculation rate of 0%) removal efficiency for TKN and NH4-N during summer is comparable to those measured in winter (91% ± 7%, 87% ± 12% and 92% ± 5%, 90% ± 7% for TKN, NH4-N in summer and winter, respectively). This is consistent with Molle et al. (2008) and Prost-Boucle et al. (2015) who practically noticed no impact of cold temperatures (below 2 °C in the air and 6 °C in the filter, respectively) on nitrogen removal efficiency on the first stage of VFCW. However, Silveira et al. (2015) observed a significant effect of temperature on NH4-N removal between summer and spring. The effect of temperature (linked to seasons) has to be taken with care as winter season (periods of high rainfall) can have a negative effect on the hydraulic of the filter by causing a temporal clogging and thereby reducing oxygen transfers (Silveira et al. 2015). Therefore, the tendency presented in Figure 3, observed in summer (June), could be similar but in a different scale in winter.

Regarding the impact of the unsaturated zone depth on the nitrification efficiency, we see in Table 2 that the deeper is the unsaturated zone depth, the greater is the nitrification
### Table 2: Biho-Filter® plants, operation modes, concentrations and removal efficiencies

<table>
<thead>
<tr>
<th>Plant number</th>
<th>Recirculation rate</th>
<th>Number of 24-h flow composite samples</th>
<th>Season</th>
<th>Hydraulic loading rate (HLR) (m/d)</th>
<th>Inlet organic load (gCOD/m²/d)</th>
<th>TKN load (gTKN/m²/d)</th>
<th>HRT saturated zone (d)</th>
<th>Conc. (mg/L)</th>
<th>Removal efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0%</td>
<td>0%</td>
<td>200%</td>
<td>300%</td>
<td>0%</td>
<td>50%</td>
<td>100%</td>
<td>300%</td>
<td>0.05–2.2</td>
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<td>6</td>
<td>2</td>
<td>3</td>
<td>8</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

*Values between brackets are standard deviations.
efficiency. The heights of the unsaturated layers are 0.4 m and 1.0 m for the plants no. 1 and no. 3, respectively, and the respective nitrification efficiencies are 47% and 87% (for a recirculation rate of 0% and the same season). This is in accordance with what is found in literature: 62% and 81% of ammonium removal for filtration depths of 0.4 m and 1.0 m, respectively (Millot et al. 2016). However, beyond 0.6 m Molle et al. (2008) did not observe any improvement of nitrification.

We stress out that increasing the depth of the unsaturated zone will improve nitrification but at the same time can induce carbon limitation for denitrification (low COD/NO₃-N ratio) (Millot et al. 2014) and a large nitrate concentration will limit the necessary decrease of redox potential for denitrification (Šima et al. 2009).

**TN removal**

Different TN removals were observed according to tested configurations. While we observed that denitrification of any nitrate formed cannot be complete, TN removal depends strongly on the previous nitrification efficiency, the availability of easily biodegradable carbon and the HRT in the saturated anoxic zone (redox potential varied between −120 mV and +40 mV/SHE (Standard Hydrogen Electrode) during a complete feeding/resting cycle, data not shown). Langergraber et al. (2009) assumed that with 80% nitrification efficiency in the unsaturated zone the quantity of nitrates available will be adequate to denitrification in the saturated zone. Moreover, Prigent et al. (2013) recommended choosing the height of the saturated zone to ensure a contact time greater than 0.4 day on the filter in operation.

Figure 4 presents the denitrification efficiency according to COD/NO₃-N ratio value at the inlet of the saturated zone and HRT in the saturated zone. The theoretical NO₃-N removal efficiency is calculated with Equation (1).

\[
R_{\text{NO}_3,N} = \frac{C_{\text{NO}_3N-\text{in}} - C_{\text{NO}_3N-\text{out}}}{C_{\text{NO}_3N-\text{in}}} \quad (1)
\]

where \( R_{\text{NO}_3,N} \) (%) is the theoretical NO₃-N removal efficiency in the saturated zone, \( C_{\text{NO}_3N-\text{in}} \) (mg/L) is the theoretical NO₃-N concentration produced by nitrification in the unsaturated zone, \( C_{\text{NO}_3N-\text{out}} \) (mg/L) is the NO₃-N concentration measured at the outlet of the Biho-Filter® plants.

The NO₃-N concentration at the inlet of the saturated zone was estimated by subtracting the TKN concentration measured at the outlet of the plants to the TKN concentration measured in wastewater (we assumed that no nitrogen is stored in the filter and all the organic nitrogen and ammonium is ammonified and nitrified, respectively). The COD concentration used for calculating the COD/NO₃-N ratio at the inlet of the saturated zone was evaluated assuming that 80% of total COD in wastewater is removed in the unsaturated zone (Morvannou et al. 2015).

Figure 4 shows that the denitrification rates are in average higher for COD/NO₃-N ratios greater than 2. We also see for this ratio that the longer the HRT, the higher the denitrification rate. However, for an HRT of less than 0.75
day and no limiting carbon the NO$_3$-N removal efficiency is still below 60% for all ratios, even ignoring the two lowest denitrification rate values with COD concentrations very low (carbon limitation).

Denitrification is statistically slightly more correlated to the HRT than to the COD/NO$_3$-N ratio (Pearson test; correlation coefficient $= 0.46$, $p$-value $= 0.0026$ and correlation coefficient $= 0.37$, $p$-value $= 0.013$, respectively) and a minimal HRT of 0.75 day seems to be the minimum necessary but not sufficient for COD/NO$_3$-N ratio lower than 3. Recent studies, in fact, showed that the depth of the saturated zone, and therefore the HRT in this zone, plays an important role in TN removal. Using a saturated zone of 0.4 m instead of 0.2 m increases TN removal of 5–10% (Prigent et al. 2016). As well, Silveira et al. (2015) observed that by increasing the height of the saturated zone from 0.15 m to 0.25 m the TN removal is higher (35% and 58%, respectively), as well as for the dissolved COD (36% and 50%, respectively). Nevertheless, most of the studies on the potential of denitrification indicated that it is the lack of carbon which is the limiting factor for denitrification (Vymazal & Kröpfelova 2011; Tanner et al. 2012; Prigent et al. 2015). According to Langergraber et al. (2009) using a particle size of 2–3.2 mm for the unsaturated zone enable to not completely remove the organic matter and so enough organic matter remains for denitrification in the saturated zone.

Therefore, in order to achieve an optimal TN removal, the best equilibrium between nitrification (optimized filtration depth and recirculation) and a limited carbon removal has to be found. As a consequence, the plant no. 3, with the deeper filtering media has the lowest denitrification rate due to a high COD removal in its unsaturated zone (upper layer). At the opposite, plants no. 1 and no. 2 show no nitrate at the outlet while the remaining COD is still high (>77 mg/L).

**Effect of recirculation rate**

For the plant no. 3 (aerobic filtering media depth of 1.0 m), the low TKN load applied (<12 gTKN/m$^2$/d), combined with recirculation, drastically improves nitrification. It can rise up to 95% for a 100% recirculation rate. Recirculation dilutes wastewater while increasing nitrification on a single vertical filter (Laber et al. 1997; Prost-Boucle & Molle 2012; Prigent et al. 2015). For higher recirculation rates (300%), the nitrification shows an important decrease (77%), which is probably due to the high hydraulic loading rate of 0.7 m measured in winter. This is considered by Prost-Boucle & Molle (2012) as the maximum limit to maintain nitrification (oxygen renewal in the filter) for low temperatures (water temperature <10 °C).

The effect of increasing recirculation may hinder reaching a low redox potential within the saturated zone, thus decreasing denitrification potential. As in classical drained vertical filter, 100% of recirculation seems to be an optimum.

A compromise must be chosen, but it seems that unsaturated/saturated vertical filters are not able to punctually achieve higher TN removal than 70%.

**Solids accumulation in the saturated layer**

The TSS trapped in the saturated zone can lead to a clogging of the bottom of the filter over time. The VSS/TSS
ratio of $61 \pm 5\%$ calculated from the samples taken during the second discharge and the high dissolved salt content (700 mg/L in average) highlight the TSS mineralization that occurs in the saturated zone. Moreover, the HRT calculated at a time interval of 1 year were substantially similar, so it is assumed that the porosity has not evolved.

During the two respective discharges, 30% and 53% of the water of the saturated zone was withdrawn. Nevertheless TSS concentrations measured after the discharges in the piezometers indicate that there is still some TSS in the saturated zone of the plant no. 1.

It is recommended to proceed every year to a draining of the filter and to return the extracted sludge to the inlet sump and then to the filters by pumping. It is not necessary to perform a complete draining of the saturated zone since most of the TSS leaving the filter are evacuated in the first 5 min of the draining. Furthermore, in addition to the low redox potential conditions promoting the development of denitrifying bacteria, TSS forming a deposit in the saturated layer may play a significant role in denitrification. The complete draining of the saturated part of a Biho-Filter® could, therefore, involve a decrease in the denitrification effectiveness. Further studies should be conducted to determine the best way to achieve a TSS draining operation to prevent clogging without affecting the denitrification rate.

CONCLUSION

An optimized ‘stacked’ French design has shown high removal efficiencies for COD, BOD$_5$, and TKN which enable us to guarantee outlet concentrations of 70 mg/L, 15 mg/L, 15 mg/L and 25 mg/L for COD, BOD$_5$, TSS and TKN, respectively, and a maximum of 60% of TN removal. The filtration depth and recirculation rate are of importance for nitrification mainly with an optimal recirculation rate of 100%. Good denitrification in the saturated zone needs at least a COD/NO$_3$-N ratio at the inflow of the saturated zone and a HRT higher than 2 and 0.75 d, respectively. In order to avoid solids accumulation in the saturated zone, an annual draining is recommended to wash them out.

The first results obtained with this kind of filter enable us to achieve similar treatment results for COD, BOD and TSS with a lower global footprint than the classical two-stage French design plus an appreciable TN removal.

REFERENCES


Mercoiret, L., Molle, P. & Forquet, N. 2010 Domestic wastewater characteristics in French rural areas: concentrations and ratios for treatment plant under 2000 population equivalent (120 kg of BOD5 a day). In: 3rd International Smallswat Congress, Seville, Spain.


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