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1 **Effects of design and operational parameters on ammonium**
2 **removal by single-stage French vertical flow filters treating**
3 **raw domestic wastewater**

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15 **Abstract**

16 Four pilot-scale single-stage vertical flow filters (of 2.25m² each), treating raw domestic
17 sewage, were studied over 20 months in order to assess the impact of different designs
18 and operational conditions on treatment efficiency. One of them was designed and
19 operated as a standard 1st stage "French" vertical flow constructed wetland unit. The
20 other 3 pilots differed from the standard pilot with respect to the filtration depth, the

21 loading rate or the partial replacement of gravel by zeolite (chabazite), respectively. The
22 pilots were monitored by analysing 24-hour flow-weighted composite samples for TSS,
23 COD_{tot}, COD_d, ammonium, nitrate and carbonate. All pilots showed a high ability to
24 remove TSS and COD_{tot}, with average removal of 81% and 75%, respectively.
25 Increasing the depth of the filtration layer from 40 to 100 cm allowed to significantly
26 improve ammonium removal (81%), whereas the simultaneous increase in hydraulic
27 and organic loads resulted in a deterioration of ammonium and COD_d removals (44%
28 for both parameters). Using zeolite did not induce any observable improvements in
29 ammonium removal under the conditions of the study.

30 *Keywords* : Ammonium, Vertical flow constructed wetland, Domestic wastewater,
31 Design

32 **I) Introduction**

33 Constructed wetlands (CWs) for wastewater treatment met an increasing worldwide
34 interest during the past three decades because of their performances, low investment and
35 operational costs and their environmental friendly image. Moreover, this technique is
36 efficient to treat various kinds of effluents such as domestic wastewater, industrial
37 wastewater or combined sewer overflows, etc. (Ávila *et al.*, 2013; Wu *et al.*, 2015;
38 Meyer *et al.*, 2013).

39 The classical design of "French CW systems" treating raw domestic wastewater (Molle
40 *et al.*, 2005) consists of two vertical flow constructed wetland (VFCWs) stages
41 operating in a sequential mode of feeding and rest periods (3.5 days and 7 days,
42 respectively). The first stage (1.2 m²/population equivalent), composed of three parallel

43 filters filled with gravel, is fed by batches of raw screened wastewater. Most of the
44 suspended solids and a part of the dissolved pollution (organic matter and ammonium)
45 are removed at this stage. The second stage (0.8 m²/pe divided in 2 parallel units) filled
46 with sand ensures a further treatment of dissolved pollution under aerobic conditions.
47 This configuration allows high removal performances on COD_{tot}, TSS and TKN,
48 namely over 90%, 95% and 85%, respectively (Morvannou *et al.*, 2015) and also easier
49 sludge management than other conventional processes. Besides, "French systems" have
50 a high tolerance to variation of hydraulic and organic loads (Molle *et al.*, 2006; Arias *et*
51 *al.*, 2014).

52 TKN removal is dependent on various parameters such as wastewater composition,
53 design considerations (media characteristics, design loads...) or external parameters
54 (maintenance, climate). Proper design and optimal operation are needed in order to
55 provide favourable conditions for nitrification. Molle *et al.* (2005) reported that a
56 minimum surface area of 2 m²/p.e. was required in order to achieve full nitrification for
57 a two-stage VFCW configuration. This may be a problem for larger units or when land
58 availability is limited. Recirculation has been reported to improve TKN removal
59 performance (Prigent *et al.*, 2011). Nevertheless, recirculation increases hydraulic loads
60 and can thus negatively affect oxygen transfers. Prost-Boucle and Molle (2012)
61 proposed to limit the hydraulic load to 0.7m/d on the filter in operation in order not to
62 affect nitrification. Oxygen transfer can be increased by implementing passive or active
63 aeration systems (e.g. tidal flow (Sun *et al.*, 2005) or forced bed aeration (Boog *et al.*,
64 2014; Foladori *et al.*, 2013; Nivala *et al.*, 2013)). However, such intensifications lead to
65 additional operating costs (Austin and Nivala, 2009).

66 Current methods for design improvement appear to favour more complex and more

67 intensified systems. The objective of the present study was to assess the extent of
68 removal performance improvement by adapting design parameters without increasing
69 energy consumption. Since nitrification is known to be highly sensitive to several
70 operational conditions such as oxygen transfer into the filter, hydraulic and organic
71 loads or the feeding strategies, it was used as an indicator for design optimisation. Four
72 pilot-scale French VFCWs were monitored over 20 months for this purpose. One of
73 them was designed and operated as a standard 1st stage filter according to the French
74 guidelines (Molle *et al.*, 2005) in order to serve as a reference. The design parameters
75 tested were the filter depth (0.4 to 1.0 m), the use of zeolite (chabazite) as filter media
76 and the hydraulic and organic loading rates.

77 **II) Materials and Methods**

78 **Experimental setup**

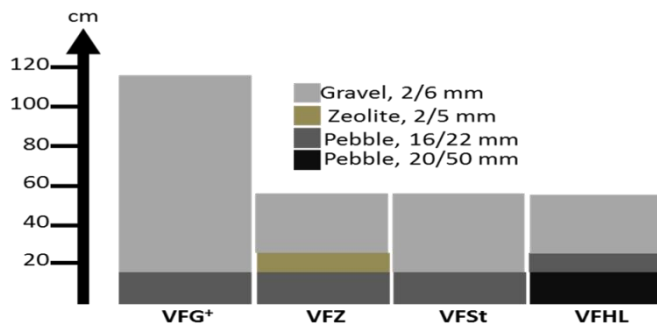
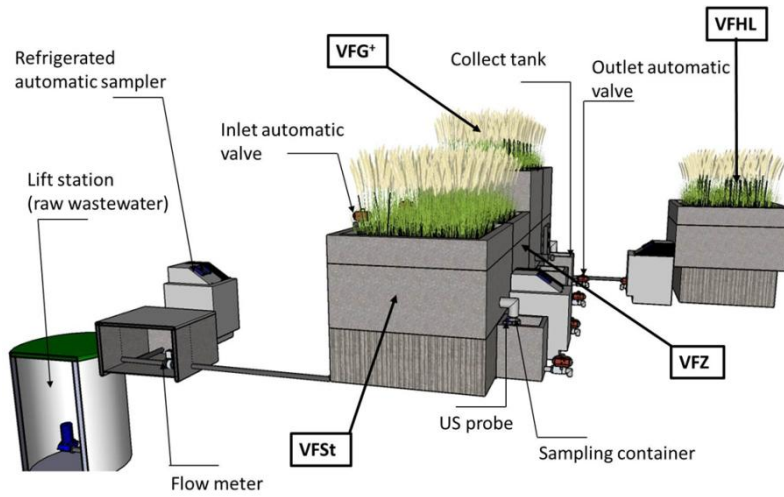
79 Four vertical flow pilot filters of 2.25 m² each were monitored for 20 months, from
80 March 2014 to October 2015. One of them, denoted as Vertical Flow Standard (VFSt),
81 was designed and operated as a standard 1st stage "French" VFCW unit. The other 3
82 pilots differed from the standard pilot with respect to the filtration depth (Vertical Flow
83 Gravel⁺, VFG⁺), loading rate (Vertical Flow High Load, VFHL) or a partial replacement
84 of gravel by zeolite (Vertical Flow Zeolite, VFZ), respectively.

85 The pilots were all composed, from bottom to the top, of a 15-cm-deep drainage layer
86 made of 16/22 mm grain size cobbles and a filtration layer whose characteristics are
87 given in Table 1. To avoid particulate migration from the filtration layer to the drainage
88 layer in the VFHL pilot, a 10-cm-deep transition layer (grain size 16/22mm) was

89 implemented above the 15-cm-deep drainage layer which was composed of 20-50 mm
90 cobbles as shown in Figure 1.

91 The pilots were operated outdoors on an experimental site located at the site of a
92 domestic wastewater treatment plant (Jonquerettes, south east of France). This facility
93 allowed us to assess the performance of VFCWs for the treatment of real raw domestic
94 wastewater screened at 20 mm under Mediterranean climate.

95 A sludge deposit layer was progressively formed at the surface of the filters by
96 accumulation of filtered particles (up to a thickness of 3cm at the end of the monitoring
97 period). The pilots were planted in September 2013 with one year old plantlets of
98 *Phragmites australis* at a density of 6 plants.m². According to French guidelines, the
99 pilots were fed for 3.5 days and rested for 7 days. During the feeding periods, 18
100 batches of 2 cm were applied daily (2 m³.h⁻¹), except for the high load pilot VFHL
101 where 32 batches a day were applied which was considered as the highest acceptable
102 hydraulic load based on full-scale observations. The monitoring started after a
103 commissioning period of five months which was meant to allow for the establishment of
104 microorganisms and reeds.



105

106 **Figure 1** Experimental setup and design characteristics

107 **Table 1** Characteristics of the pilot design

Pilot units	Studied parameters	Filtration layer	Passive aeration location (cm) ^{(1)/(3)}	Hydraulic load (m ³ .m ⁻² .d ⁻¹) ⁽²⁾	Organic load (gCOD.m ⁻² .d ⁻¹) ⁽²⁾
		Material	Depth (cm)	Sampling systems (cm) ⁽¹⁾	
(VFSt)	Unit of reference	Gravel 2/6 mm	40	10 and 30	Bottom 0.36 234 (62)

Deep Filtration (VFG+)	Effect of filtration depth	Gravel 2/6 mm	100	10, 20, 40, 60, 80	Bottom, 30 and 60	0.36	240 (80)
High Load (VFHL)	Effect of hydraulic and organic loads	Gravel 2/6 mm	30	10	Bottom and 30	0.64	536 (276)
Zeolite Chabazite (VFZ)	Effect of sorbent materials	Gravel 2/6 mm Zeolite 2/5 mm	30 + 10	30 and 40	Bottom	0.36	237 (71)

108 ¹ Depth from the filter surface

109 ² Loads are calculated for the filter in operation

110 ³All drains are connected to the atmosphere, resulting in a passive aeration from the
111 bottom on the length of the filter. The intermediate passive aeration systems consist of
112 drilled pipes, with connection to the atmosphere, which are crosswise implemented in
113 the filtration layer of the pilot.

114 **Preliminary validation of reference pilot**

115 A preliminary step of validation of the reference unit was required to verify whether the
116 treatment performance of the VFSt was in the range of those usually observed at full-
117 scale 1st stages of a classical French VFCW. For that purpose, inlet and outlet

118 concentrations of the VFSt were compared with a set of data collected from three full-
119 scale treatment plants with the same design (part of data from Morvannou *et al.*, 2015).
120 The inflow of each pilot was also compared in order to confirm that they received the
121 same wastewater during the study so that their performance could be compared.

122 **Experimental monitoring of the pilots**

123 The inlet and outlet water concentrations were assessed for the first and the last day of
124 the feeding periods using refrigerated samplers (Ponsel, ISCO 4700 and Hach, Bühler
125 2000). 24-hour flow-weighted composite samples were taken from the outlet while, for
126 the inlet, 24-hour composite samples were obtained from one grab sample per batch.
127 Intermediate 24-hour composite samples were taken from different depths (see Table 1)
128 and analysed. Pore water was collected during infiltration by PVC gutters (9 cm and 30
129 cm of width and length, respectively), located at different depths within the filtration
130 layer, and then stored into pre-acidified 25L polyethylene containers. Each pilot was
131 evaluated for total and dissolved COD (COD_{tot} and COD_d, respectively), TSS, NH₄-N,
132 NO₃-N and CaCO₃ using quick method tests (Hach).

133 Online measurements were also carried out for continuous monitoring of hydraulic and
134 treatment performance dynamics. Inlet flows were determined using an electromagnetic
135 flowmeter (Siemens, SITRANS MAG 5100W) whereas outlet flows were measured
136 with ultrasonic probes (Pil, P43-F4V-2D1-D0-330E) by the rise of the level of effluent
137 drained into a collecting tank. Nitrogen concentrations (NH₄-N and NO₃-N) were
138 continuously monitored at the inlet and the outlet of each pilot at time intervals of 15
139 and 2 minutes, respectively, using ion selective electrodes (AN-ISE, Hach).

140 The monitored data were used to compare the performance of pilots. For this purpose,

141 removal rates were calculated on mass basis considering the measured concentrations
142 and the inlet volumetric flows.

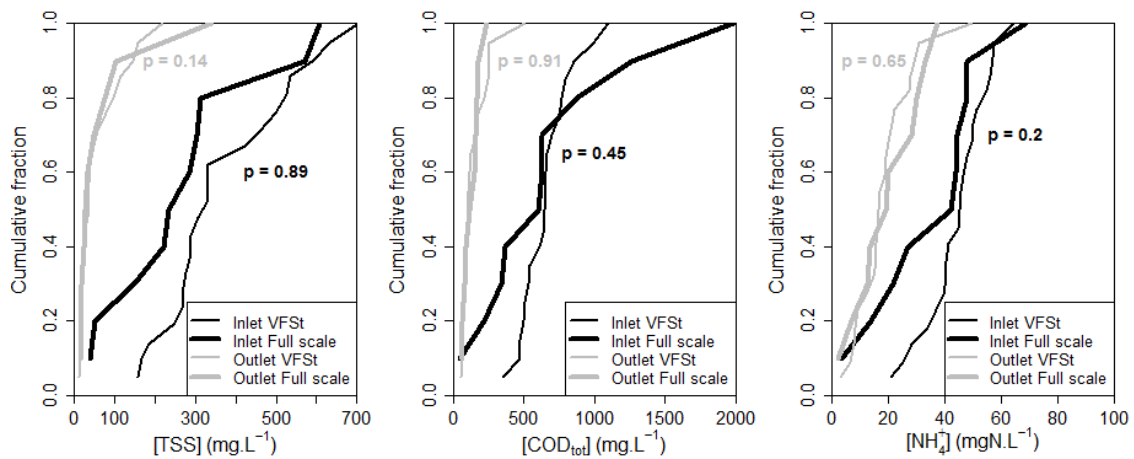
143 **Statistical analysis**

144 Experimental results were statistically analysed using R software. Kruskal Wallis tests
145 were carried out on the full set of data, in order to validate that all pilots received the
146 same influent, while Wilcoxon and Student tests were used for pair-wise comparison of
147 each pilot with the reference unit. Significant difference was established at p-value \leq
148 0.05.

149 **III) Results and Discussions**

150 **1) Validation of control pilot VFSt**

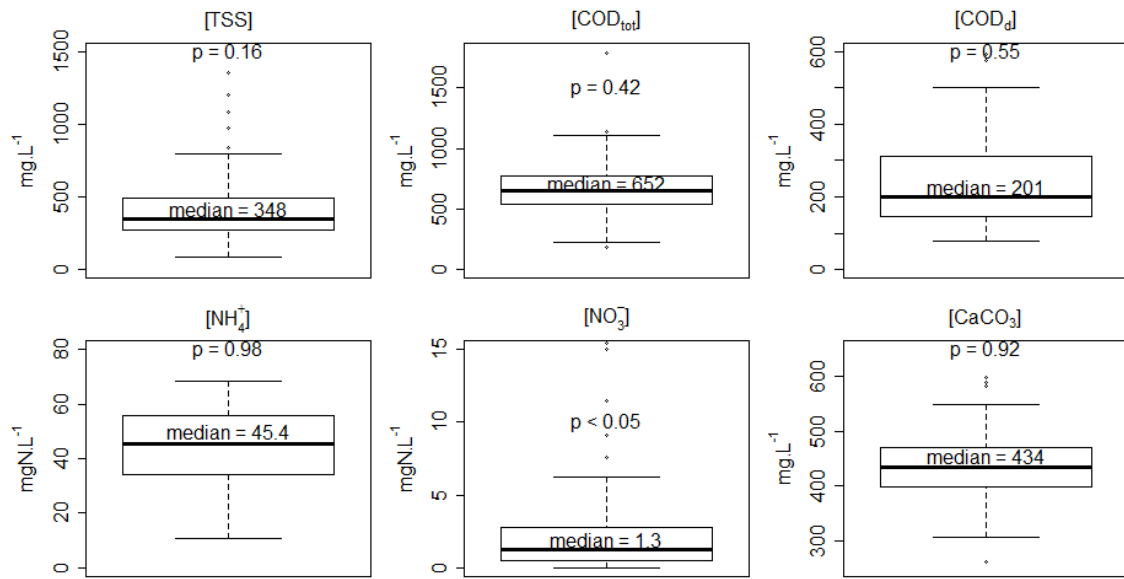
151 The treatment performance of VFSt was compared to full-scale classical French first
152 stage filters (Morvannou *et al.*, 2015) with respect to TSS, COD_{tot} and ammonium as
153 shown in Figure 2. The results of Wilcoxon statistical comparison between VFSt and
154 full-scale VFCWs confirmed that the reference pilot VFSt of the study could be
155 considered as a standard filter. Moreover the pollutant concentrations in the inlet
156 (TKN/COD_{tot}, TSS/COD_{tot} and TKN/NH₄-N) were in the range of what was reported
157 from a survey of almost 3000 treatment plants of small French communities (Mercoiret
158 *et al.*, 2010).



159

160 **Figure 2 Influent and effluent composition of VFSt and Full scale treatment plants (depth of 40cm)** (p-values
 161 are the outcome of a Wilcoxon test comparing data from pilot and full-scale systems)

162 Figure 3 shows the distribution of influent composition over the whole study without
 163 distinction between pilots. It can be observed that inlet composition during the study
 164 was similar for all pilots, as confirmed by the Kruskal Wallis test comparing average
 165 inlet concentrations of each pilot. It was therefore relevant to compare them with the
 166 VFSt filter. Nitrate concentrations however were significantly different. This can be
 167 explained by a few high values measured in the influent which modified the average
 168 value.



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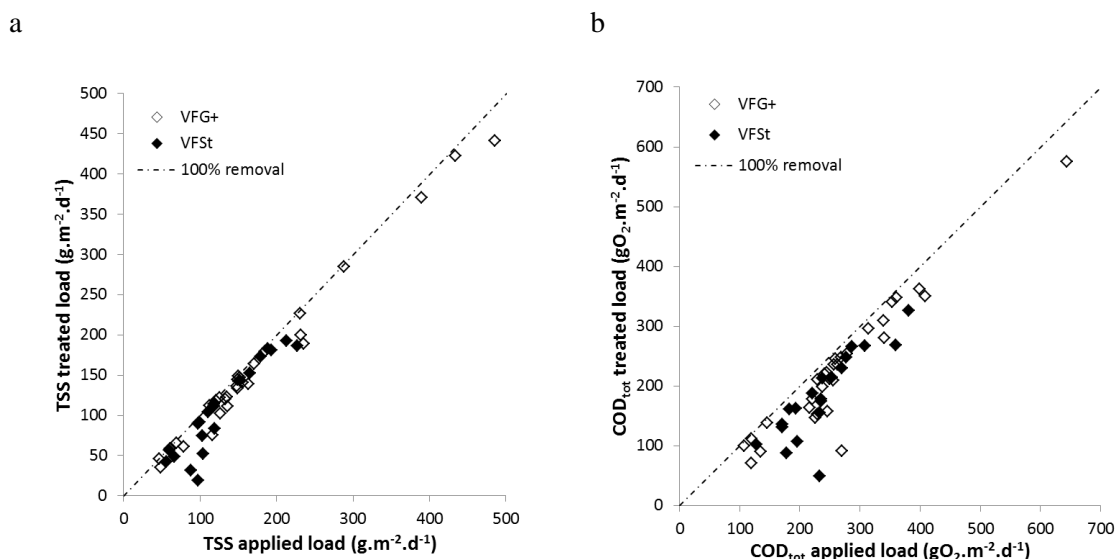
170 **Figure 3 Influent wastewater composition during the study** (note that one TSS outlier over 3000mg/L, one
 171 COD_{tot} outlier over 1500mgO₂/L, one COD_d outlier over 1000mgO₂/L and four NO₃⁻ outliers between 10 and
 172 20mgN/L are not shown for visibility reasons). P-values are the outcome of a Kruskal Wallis test comparing data
 173 from pilot full dataset.

174

2) Influence of filtration depth

175 Increasing the filtration layer depth from 40 to 100 cm did not significantly improve
 176 TSS removal ($p = 0.09$). Median TSS removal efficiency was 92% and 91% for VFSt
 177 and VFG⁺, respectively, falling within the range of removal rates usually observed for
 178 first stage filters in French VFCW system (Morvannou *et al.*, 2015, Paing and Voisin,
 179 2005). Molle *et al.* (2005) and Paing & Voisin (2005) reported that TSS removal mostly
 180 occurred at the surface of the first stage filter. Figure 4a shows the effect of applied load
 181 on treatment efficiency. It can be seen that TSS removal was linear even for high loads.
 182 The lowest removal rates (especially for the VFSt at loads of 100 g.m⁻².d⁻¹) were
 183 obtained within the first five months after the commissioning period when the sludge
 184 deposit layer was still very thin. TSS removal efficiencies were thereafter higher than
 185 90%. This observation confirmed the positive effect of the sludge deposit layer
 186 thickness on filtration performance (Molle *et al.*, 2005).

187 The effect of filtration depth on COD_{tot} removal was quite similar as for TSS (Figure
 188 4b). This was mainly explained by the fact that most of COD_{tot} was under particulate
 189 form ($COD_d/COD_{tot} = 0.3$ in this study).



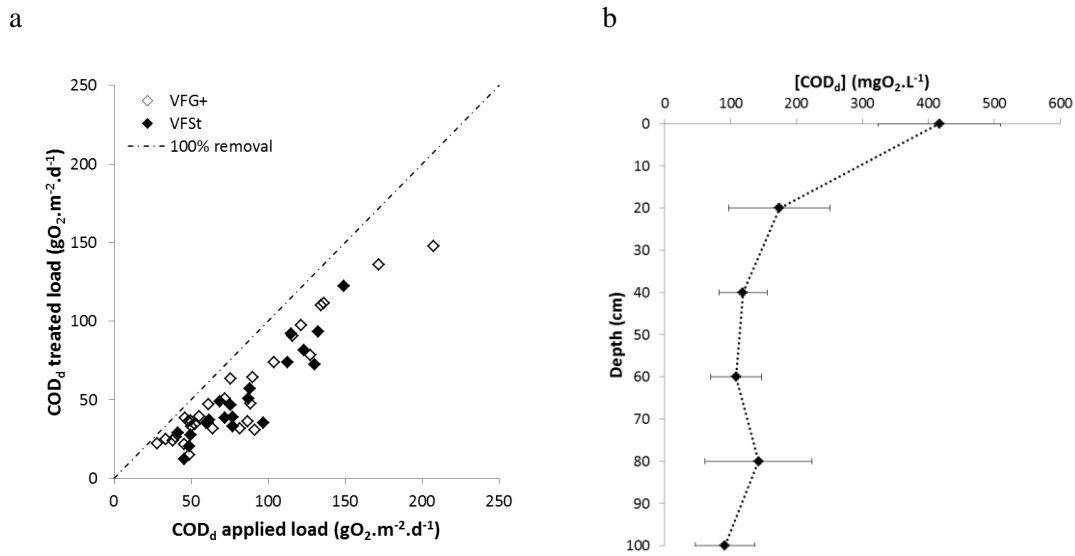
190 **Figure 4** Treated TSS (a) and COD_{tot} (b) loads according to the applied TSS and COD_{tot} loads, respectively

191 Figure 5a showed that, within the range of COD_d loads applied in this study, the
 192 reference pilot VFSt performed similarly to the deep filter pilot VFG⁺. COD_d removal
 193 was not statistically improved by increasing the filtration depth ($p = 0.06$) although a
 194 slightly better removal was observed for VFG⁺ (59% and 66% for VFSt and VFG⁺,
 195 respectively). Even though the implementation of a deeper filtration layer did not result
 196 in a statistically significant improvement of COD_d removal, it allowed a slight
 197 improvement of the outlet concentration (92.5 and 73.1 mg.COD_d⁻¹ on average for VFSt
 198 and VFG⁺, respectively).

199 Around 60% of COD_d was degraded within the upper 20 cm of the filter as shown by
 200 the depth profile presented in Figure 5b. The removal rate then strongly decreased up to
 201 40 cm-depth to become almost negligible with further depth. Morvannou *et al.* (2014)

202 reported that the heterotrophic community was mainly located in the sludge deposit and
203 the upper part of the filtration layer in French first stage VFCW. Their similar
204 performance in COD_d removal was consistent with the distribution of heterotrophic
205 bacteria of Morvannou et al. (2014). Olsson (2011) carried out a similar experiment
206 with VFCWs filled with different media (gravel or sand) and fed with pre-treated
207 wastewater. The depth profile of total organic carbon (TOC) in sand revealed 68%
208 removal at 20 cm-depth, which was very close to the COD_d profile observed in the
209 present study. For gravel however, the profile was quite linear until 80 cm deep,
210 suggesting that heterotrophic community can colonize deeper zones of filtration. This
211 different depth profile with gravel may be explained by the fact that the gravels used in
212 Olsson's work were coarser than in this study (4/8 mm and 2/6 mm, respectively) and
213 the influent was pre-treated in a settling tank. In our study, the infiltration rate was thus
214 probably lower. The similar depth profile between our study and the sand VFCW (1/3
215 mm) of Olsson shows the positive impact of sludge deposit on the hydraulics of the
216 French systems (Molle *et al.*, 2006).

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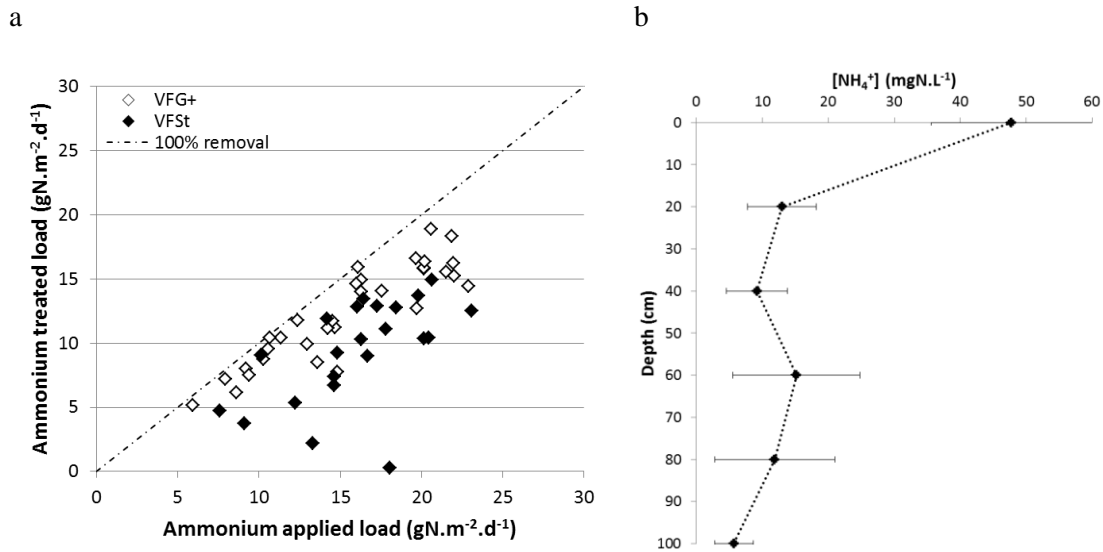


219 **Figure 5 Treated COD_d loads according to COD_d the applied loads (a) and COD_d depth profile during feeding**
 220 **cycle for the VFG⁺ pilot (Six 24-hour composite samples) (b)**

221 As illustrated in Figure 6a, ammonium removal efficiency was significantly improved
 222 by increasing the filtration depth ($p = 0.01$). It increased from 62% in 40cm-deep
 223 reference pilot VFSt to 81% in 100cm-deep VFG⁺. Ammonium removal was linear
 224 within the applied load between 5 and 25 gNH₄-N.m⁻².d⁻¹.

225 We also observed a significantly different consumption of alkalinity ($p = 0.04$) and
 226 production of nitrate ($p = 0.001$). While VFSt had a mean nitrate production of 10.1
 227 gN.m⁻².d⁻¹ and removed 57.1 g.m⁻².d⁻¹ of calcium carbonate on average, increasing the
 228 filtration depth from 40 cm to 100 cm improved the phenomena by almost 50% (14.1
 229 gN.m⁻².d⁻¹ and 75.9 g.m⁻².d⁻¹ of nitrate production and CaCO₃ removal, respectively).
 230 These observations, along with the results on ammonium removal discussed above,
 231 revealed that a deeper filtration layer enhanced the nitrification rate.

232



233 **Figure 6 Ammonium treated loads according to the ammonium applied loads (a) and ammonium depth profile**
 234 **during feeding cycle for the VFG+ pilot (Six 24-hour composite samples) (b)**

235 The depth profile of ammonium concentration (Figure 6b), carried out on 6 24-hour
 236 composite samples in the last stages of operation, showed that the upper 40 cm achieved
 237 about 75% of removed ammonium, while the overall performance was 87% at 100 cm
 238 deep. These results are in accordance with previously published works. Thus, Torrens *et*
 239 *al.* (2009) observed a higher TKN removal when increasing the filtration depth of a
 240 sand VFCW (from 69% to 78% at 25 cm and 65 cm, respectively) and Molle *et al.*
 241 (2008) reported a negligible improvement of TKN removal when increasing the
 242 filtration depth of the first stage of a French system from 60 cm to 80 cm. These
 243 observations may be attributed to the fact that autotrophic bacteria are mainly located in
 244 the sludge deposit and the upper 30 cm of the filtration layer as reported by Morvannou
 245 *et al.* (2014).

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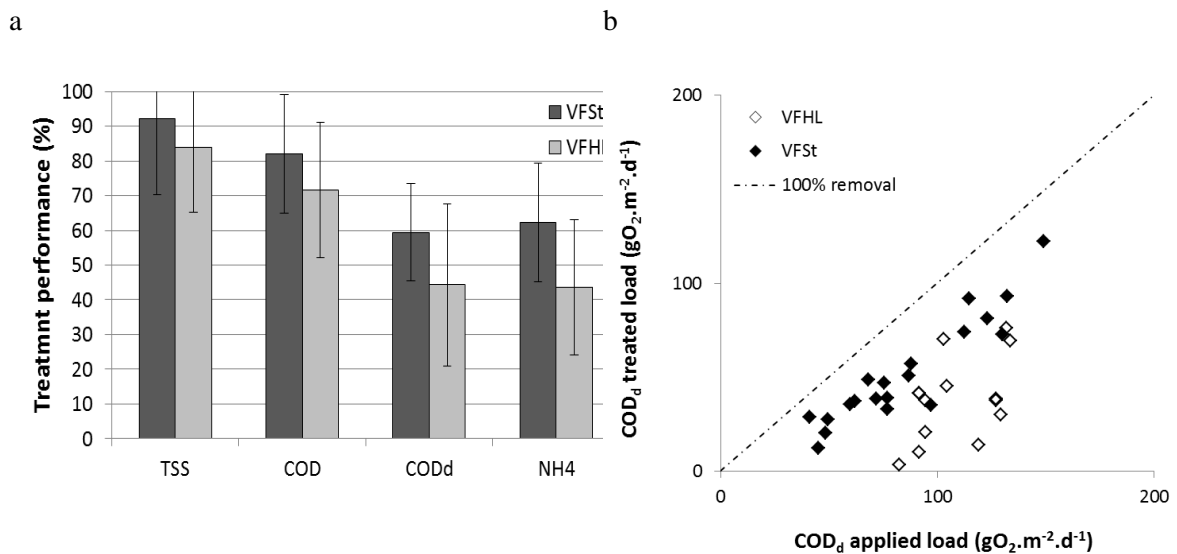
248

3) Effects of hydraulic and organic loads

249 Figure 7a presents the removal efficiency observed for TSS, COD_{tot}, COD_d and NH₄ in
250 the reference (VFSt) and high load (VFHL) pilots. VFSt and VFHL showed similar TSS
251 removal (92% and 84% respectively) indicating that hydraulic and organic loads had no
252 significant influence on this parameter within the studied range ($p = 0.12$). Analytical
253 data were exploited in terms of concentrations since the pilots did not receive identical
254 loads.

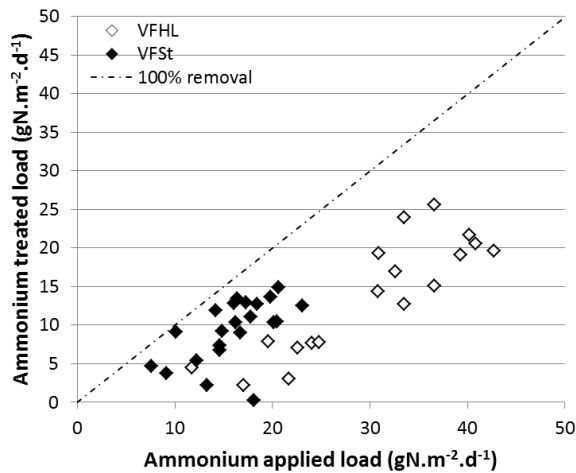
255 COD_d removal was significantly impacted ($p=0.04$). It was reduced from 59% in VFSt
256 to 44% in VFHL as shown in Figure 7a. This observation may be explained by the
257 hydraulic changes induced by the increase of the loads. More frequent feedings resulted
258 in an increase of ponding time, a decrease of water retention time (Molle *et al.*, 2006)
259 and thus hindered oxygen renewal within the filter. This in turn was detrimental for
260 aerobic microbial activity. The impact of hydraulic conditions is well described in
261 Figure 7b which shows the COD_d removal in relation with loads. The removed load was
262 lower with VFHL than with VFSt for similar applied organic loads.

263



265 **Figure 7 Treatment performance for global pollutants (a) and COD_d treated loads according to the COD_d**
 266 **applied loads (b)** (Note that a selection in VFHL data was carried out in order to study treatment efficiency for
 267 similar organic loads but different hydraulic loads)

268 A significant reduction of ammonium removal ($p = 0.007$) occurred when increasing the
 269 hydraulic load from 0.36 cm.d^{-1} to 0.64 cm.d^{-1} . Performance dropped from 62% to 44%
 270 for VFSt and VFHL, respectively (Figure 7a). Ammonium removal related to applied
 271 loads in VFSt and VFHL is shown in Figure 8. For similar applied ammonium loads
 272 (between 5 and $25 \text{ gN.m}^{-2}\text{d}^{-1}$), VFHL exhibited lower removal capacity than VFSt. This
 273 might be explained by the lower oxygen transfer capacity of the system, lower water
 274 retention time as well as a higher saturation of ammonia adsorption sites due to less
 275 time for nitrification between batches.



276

277 Figure 8 Ammonium treated loads according to the ammonium applied loads

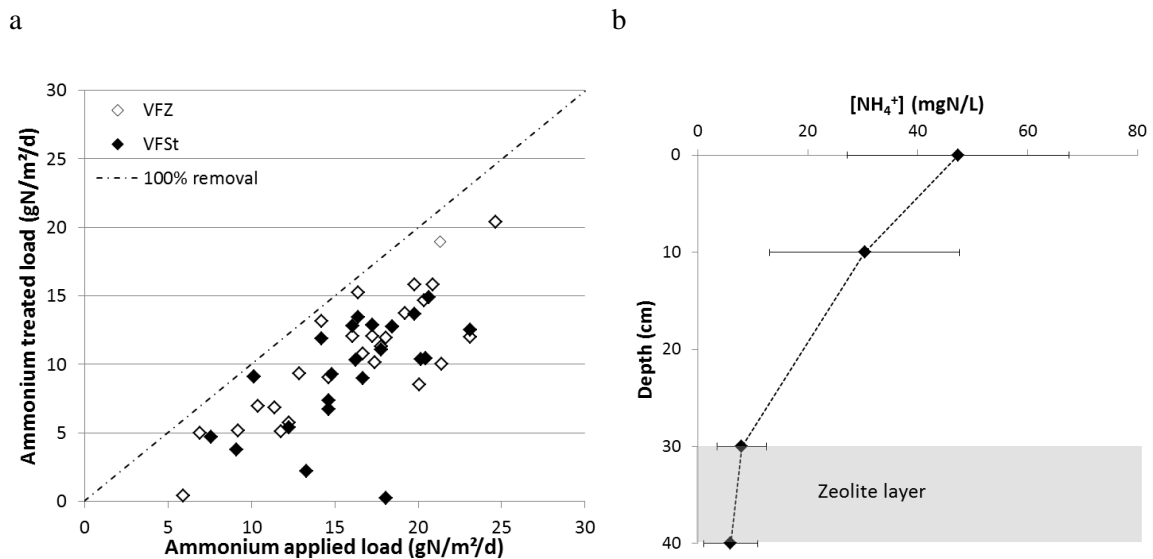
278 **4) Effect of the implementation of a sorbent material**

279 The implementation of zeolite at the bottom of the filtration layer did not result in a
 280 significant improvement of ammonium removal ($p = 0.29$) regardless of the applied
 281 load as shown in Figure 9a. VFSt and VFZ achieved 62% and 68% of ammonium
 282 removal, respectively. This observation was consistent with Stefanakis and Tsihrintzis
 283 (2009) who reported that no significant improvement occurred in TKN removal by
 284 using zeolite in VFCW.

285 Knowing the cationic exchange capacities of zeolite (Erdoğan and Ülkü, 2011;
 286 Malekian *et al.*, 2011; Huang *et al.*, 2010; Ivanova *et al.*, 2010), we can observe that
 287 adsorption process was not efficient with the design used for VFZ. Since regeneration
 288 of sorption sites was expected to occur through nitrification of ammonium during the
 289 resting period, the progressive fouling of the media may not fully explain this lack of
 290 efficiency. The alkalinity concentrations and the pH values measured in VFZ effluent
 291 were favourable for nitrification (284 mg/L and 7.5, respectively). However, Figure 9b
 292 shows that almost no ammonium removal occurred in the zeolite layer. Different

293 possible explanations can be drawn as preferential flows, short water retention times as
 294 well as the low ammonia concentration at this stage ($< 10 \text{ mgN.L}^{-1}$). Nevertheless,
 295 Lahav and Green (1998) reported outlet ammonium concentrations lower than 1 mgN.L^{-1}
 296 ¹ with upflow mode columns fed at 40 mgN.L^{-1} . Such ammonium removal was possible
 297 by the implementation of large amount of chabazite (almost five times the amount in
 298 this study) with short contact time (2 minutes). It should be thus possible to improve the
 299 ammonium removal by increasing the zeolite fraction of the filtration layer.

300 It is also known from kinetic studies, carried out under static conditions for different
 301 contact times, that sorption increases with contact time until an equilibrium is reached
 302 (Huang *et al.*, 2010; Wen *et al.*, 2006). Therefore, limiting the outflow rate may be one
 303 possible option to improve the effect of zeolite by increasing contact time without
 304 adding more zeolite.



305 **Figure 9 Treated ammonium loads versus applied ammonium loads (a) and depth profile of ammonium**
 306 **concentration during a feeding cycle (3 24-hour composite samples) (b)** Note that the systems were drained
 307 vertical flow filters which were therefore operated under unsaturated conditions.

308 **IV) Conclusion**

309 This study aimed at identifying the leverage actions in order to reduce the treatment
310 footprint of VFCW. The respective impact of design criteria and operation conditions
311 on the ability of a 1st stage of VFCW to perform treatment of different pollutants (TSS,
312 COD_d, ammonium), from raw domestic wastewater, were assessed for this purpose.

313 TSS removal was not affected by the studied modifications of design or operational
314 parameters since it was mainly a surface mechanism. Therefore, reduction of the 1st
315 stage surface would not result in a drop in particles treatment efficiency. Nevertheless,
316 the decrease in surface of treatment (from 0.4 m²/p.e./bed to 0.25 m²/p.e./bed,
317 respectively) would cause an increase in daily hydraulic load (from 0.36 m.d⁻¹ to 0.64
318 m.d⁻¹) which showed significant adverse effects on COD_d and ammonium removal
319 (from 59% to 44% and from 62% to 44%, respectively) because of the shorter contact
320 time as well as lower oxygen renewal within the filter.

321 The lower removal of COD_d and ammonium observed when decreasing the surface of
322 the 1st stage may be partly counterbalanced by the implementation of deeper filtration
323 layer. Ammonium removal was actually raised from 62% to 81% and COD_d removal
324 was improved from 59% to 66% when filtration depth increased from 40 cm to 100 cm.
325 Nevertheless, the relation between gain of performance and depth of filtration was low,
326 especially when the filtration layer was deeper than 60 cm since the microbial
327 community was mainly located in the upper part of the filtration layer. In addition, a
328 deeper filtration layer enabled to maintain a more constant efficiency which might be
329 valuable when fluctuation of performance is observed (i.e. when temperature variations,
330 over year, are wide).

331 Furthermore, despite its theoretical ion exchange capacity, zeolite implementation in the
332 filtration layer did not allow to reach the expected improvement of ammonium removal
333 for the assessed characteristics of design and operation. Higher zeolite content might
334 provide different conclusions but would result in prohibitive extra-costs (zeolite was
335 almost 5 times more expensive than gravel). The implementation of such reactive
336 material, as suitable alternative to intensification, should not be further considered
337 unless the operation conditions allowed the optimal use of exchange capacity. Further
338 studies are thus necessary to determine the best design and operational conditions for its
339 efficient use.

340 In conclusion, it seems difficult to reach low discharge levels with a single stage of
341 VFCW treating domestic wastewater. However, surface requirements may be reduced to
342 0.25 m²/p.e./bed if a second stage ensures the final treatment of remaining pollution and
343 if filtration depth is also used as an adjustment parameter.

344 **V) References**

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