Performance and reliability comparison of French vertical flow treatment wetlands with other decentralized wastewater treatment technologies in tropical climates

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ABSTRACT

When implementing a sanitation system, the selection of treatment process can be difficult. Beyond removal efficiency and effluent concentrations, reliability should be taken into account. This study compares reliability of French vertical flow treatment wetlands (F-VFTW) with the four main decentralized wastewater treatment technologies in small communities in the French Overseas Territories (FOT).

Analysis of 963 regulatory self-monitoring sampling campaigns performed on 213 wastewater treatment plants show that operational disruptions due to sludge loss and loss of nitrification are often reported for activated sludge technology; rotating biological contactors often suffer from weak settlement; facultative pond removal is limited by algae; and F-VFTW fulfills all the French regulatory objectives at a frequency of 90 to 95%.

In addition, the data from this study are compared to a similar database from Brazil using a statistical approach (coefficient of reliability). Amongst the eight decentralized wastewater treatment technologies evaluated, F-VFTW appears to be the most appropriate for achieving the discharge standard with a reliability close to 95%. Its reliability to face both environmental (rainfall) and social (maintenance capacities) constraints is a key parameter.

Key words | activated sludge, coefficient of reliability, constructed wetland, facultative pond, rotating biological contactor

HIGHLIGHTS

- Amongst the eight treatment processes studied in operating conditions, the F-VFTW is the most reliable.
- Extensive processes are most suited to both environmental (rainfall patterns) and social (low maintenance capacities) constraints of the FOT.
- Activated sludge is the most frequently implemented technology in the FOT, but the least reliable.

INTRODUCTION

Sanitation in most tropical areas, especially in small municipalities and rural areas, faces special challenges such as fast population growth, limited technical skills, limited financial resources, little or no sludge management solutions, and highly varying water fluxes brought by tropical rain patterns. In this context, treatment wetlands (TW) have long been touted as potential solutions for wastewater treatment in developing countries (Denny 1997; Haberl 1999; Kivaisi 2000; Zhang et al. 2014).
The French vertical flow treatment wetland (F-VFTW) fed with raw wastewater (Molle et al. 2005; Dotro et al. 2017) offers a simple solution for sludge management compared to TW systems coupled with an additional primary treatment step (such as a septic tank). There are more than 4,500 F-VFTW plants in operation in mainland France, making it the most popular TW system in the country. Adapting F-VFTW to tropical climates has recently been researched (Brazil: Lana et al. 2013; Manjate et al. 2015; Trein et al. 2019; FOT: Molle et al. 2015; Lombard-Latune et al. 2018; Lombard-Latune 2019; India: Yadav et al. 2018), including optimal vegetation selection for tropical F-VFTW (Lombard-Latune et al. 2017).

As in a classical design, sizing is based on an acceptable organic load of 350 g chemical oxygen demand (COD)/m²/d applied to the operating filter (Molle et al. 2015; Dotro et al. 2017). There are two stages of treatment in the classical design for temperate climates: the first stage has three parallel filters, each fed alternately for 3.5 days, and the second stage has two parallel units. This leads, for typical domestic wastewater treatment, to a total surface area of 2 m²/PE. The tropical design is more compact and gives a total surface area of 0.8 m²/PE. The guideline for the design of a F-VFTW for tropical climates (Lombard-Latune & Molle 2017) presents the different options: number of stages, thickness of the layers, unsaturated/saturated layers, recirculation loops and their related treatment performance (up to 90/95/90/70% concentration removal and 75/15/6/35 mg/L in effluent concentrations for COD/total suspended solids (TSS)/total Kjeldahl nitrogen (TKN)/total nitrogen (TN)) respectively.

Beyond the percentage concentration removal and effluent concentrations, which commonly represented the performances of a treatment technology, its reliability should also be taken into account when implementing a wastewater treatment plant (WWTP). Reliability can be measured as the percentage of time during which the expected effluent concentrations or removal efficiency comply with specified discharge standards or treatment targets (Niku et al. 1979; Oliveira & Von Sperling 2008; Metcalf & Eddy 2014; Von Sperling et al. 2020).

There are many uncertainties during the start-up phase of a new WWTP. The loads to be treated are generally unknown, as the design of the treatment system often occurs before the construction of the sewer network. The overall capacity can be estimated, but the quality of the raw wastewater (its dilution regarding local water use habits, rainfall and related overflow, the quality of the sewage system and the intrusion of meteoric water), is often an educated guess at best. Other uncertainties are related to the treatment technology itself: the robustness of its design, the quality of the construction and materials, the frequency and quality of the operational and maintenance tasks. These uncertainties present a risk of failure and/or unavoidable variations in performance. The probability of failure is extremely sensitive to the distribution function of the effluent concentration (Oliveira & Von Sperling 2008). Consequently, WWTPs should be designed to produce an average concentration below the relevant discharge standards. Niku et al. (1979) developed a coefficient of reliability (COR) that links the distribution function of the effluent with the targeted discharge standard and the related level of reliability to obtain an operational mean value to achieve, called the design concentration. While Niku et al. focused the use of the COR on one treatment process (activated sludge (AS), 1979, trickling filter (TF), 1982), Oliveira & Von Sperling (2008) use it to compare the reliability of six different treatment technologies based on the analysis of 166 WWTPs in Brazil.

A database was created using all the data available in the five French Overseas Territories (FOT – Martinique, Guadeloupe, Mayotte, La Réunion islands and French Guiana) for treatment plant capacities between 20 and 2,000 PE. The database was then used for the purposes of this study: (i) to compare performance in real operating conditions of the F-VFTW with the main treatment technologies implemented in the FOT; (ii) to analyze the reliability of the treatment technologies implemented in the FOT and compare them with similar wastewater treatment plants in Brazil.

**MATERIAL AND METHODS**

**Database construction**

A database of 24-hour flow composite samples was built with data from two data sources: (1) compulsory WWTP sampling as required by French regulations and (2) optional WWTP sampling conducted by local water authorities. The following analyses are commonly reported: COD, biological oxygen demand (BOD₅), TSS, TKN, ammonia nitrogen (N-NH₄), nitrite nitrogen (N-NO₂), nitrate nitrogen (N-NO₃), phosphate phosphorus (P-PO₄), total phosphorus (TP), pH, conductivity and flow measurements.

The first data source contains monitoring data as required by French regulations. These data are available...
from treatment systems in the FOT from 2012 to 2017. The number of 24-hour-flow composite samples depends on the size of the treatment plant: one every 2 years for treatment systems serving 200–500 PE, one per year for treatment systems serving 500–1,000 PE, and two per year for treatment systems serving 1,000–2,000 PE. As monitoring is not compulsory for treatment systems smaller than 200 PE, very few data are available. The second data source contains data from local water authorities who have occasionally carried out studies on specific technologies, local areas, or precise capacity. When 24-hour-flow composite sampling campaigns were conducted, these results were added to the database.

Prior to further analysis, screening and validation of the raw wastewater data was performed. The aim was to remove inconsistent data or outliers, while preserving variability and extreme realistic values that show the high variability in influent quality. The sorting methodology was adapted from Mercoiret (2010) and Morvannou et al. (2015). Reliability was evaluated statistically (principal component analysis and Chauvenet’s criterion tests) on both inlet pollutant concentrations and the ratios between them. Those ratios represent chemical equilibrium in raw wastewater, such as COD/BOD₅, TKN/COD, TSS/COD and NH₄-N/TKN. A value identified by several tests as an outlier was removed. It was an iterative process, which was carried out several times for each parameter and each ratio. It was generally stopped after the third run when the dataset was considered dense enough, in order to avoid removing extreme values that could be realistic. With a small amount of data removed (from 9 of 1,448 for COD to 23 of 684 for NH₄), the database gained in consistency (reduction of standard deviation, from 5,199 to 390 for COD and from 24 to 20 for NH₄-N). The resulting database consisted of data from 273 WWTPs and approximately 1,500 24-hour sampling campaigns (Figure 1).

AS is the most implemented treatment technology in the FOT. Uncertainties regarding the type of process remained for more than 17% of the treatment systems, which highlighted the lack of knowledge of water authorities of their own territories. They are mainly small systems (<200 PE) that are locally owned and managed. They are frequently composed of several on-site sanitation units. This is a common situation in the FOT, but urban sewer system extensions are in progress and usually plan to connect those subdivisions.

To assess performance, all the technologies with less than 10 sampling campaigns available were removed. Finally, four technologies remained: AS, rotating biological contactor (RBC), facultative ponds (FP) and F-VFTW, which represented 213 WWTPs and 963 sampling campaigns (Figure 2).

The number of sampling campaigns per WWTP is shown in Figure 3. With less than 25 samples per WWTP, the database is considered to be homogeneous as no plant is overrepresented. At a technology level, the average number of sampling campaigns per WWTP varies from 3.5 for the RBC to 10 for the F-VFTW.

Additional monitoring campaigns

To confirm the database analysis, additional monitoring campaigns were performed. Eight small WWTPs below 1,000 PE were chosen as being representative and suitable for monitoring. They were located in Martinique Island and French Guiana. Four of them were AS, two RBC and two FP. Four 24-hour-flow composite samples were collected from each WWTP between November 2017 and June 2018. The following parameters were analyzed: COD,
BOD$_5$, TSS, TKN, NH$_4$-N, NO$_2$-N, NO$_3$-N, PO$_4$-P, TP, pH, conductivity and flow. Their design was analyzed in terms of the state of the art (Von Sperling & de Lemos Chernicharo 2003). The maintenance reports were collected and studied in order to evaluate maintenance and operation.

**Coefficient of reliability (COR)**

Reliability of the treatment process was studied using the COR method by Oliveira & Von Sperling (2008) and developed by Niku et al. (1979). It is based on the lognormality of the data, which is commonly observed for WWTP data. It was tested with data from the database (AS and F-VFTW for COD, BOD$_5$, TSS and TKN).

The COR is calculated using the following equation (Niku et al. 1979):

\[
COR = \sqrt{CV^2 + 1} \times \exp\left(-Z_{1-\alpha} \sqrt{\ln(CV^2 + 1)}\right)
\]

where CV is the coefficient of variation (standard deviation divided by mean), $\alpha$ is the probability of failing to meet the standards, and $Z_{1-\alpha}$ is the standardized normal variate.

In this study, COR was used to determine the design concentration that would be required to meet a specific discharge standard with a level of reliability of 95% ($Z_{1-0.05} = 1.645$), according to the variability of the effluent concentration described in the database. The following equation was used:

\[
m_x = (COR)X_s
\]

where $m_x$ is the design concentration (mg/L) and $X_s$ is the effluent concentration as specified by the discharge standard (mg/L).

**RESULTS AND DISCUSSION**

**Performance assessment of different technologies**

The performances of the different treatment technologies are presented in terms of concentration percentage removal (Figure 4) and outlet concentrations (Figure 5). They are shown in reference to the French minimum regulation objectives for systems below 2,000 PE (concentration percentage removals of 60/60/50% for BOD$_5$/COD/TSS or outlet concentrations below 35/200 mg/L for BOD$_5$/COD).

**Biological oxygen demand**

There is no clear difference between treatment technologies when looking at concentration percentage removal as the curves follow the same pattern. BOD$_5$ represent carbon compounds easily degradable by biomass. However, effluent concentrations of AS and RBC are below 75% of compliance with the French regulation (35 mg/L), when for FP and F-VFTW they are over 90%.

**Chemical oxygen demand**

The concentration percentage removals by RBC and F-VFTW are high: only 6% of the samples are below 60% removal, the figure is twice as much for AS and triple for FP. No removal is observed for about 8% of the FP samples. For effluent concentrations, 85% of AS and RBC samples are below 200 mg/L, the figure is more than 90% for FP and close to 100% for F-VFTW.

**Total suspended solids**

About 10% of AS, RBC and FP samples show no removal of TSS. For those processes, 12–25% of the samples are below 60% concentration percentage removal, while it is 2% for F-VFTW. Regarding effluent concentrations, 35 mg/L is achieved by less than 65% of AS, RBC and FP samples but by about 90% of F-VFTW.
Figure 4 | Percent concentration removal for main pollutants of concern by the four different treatment technologies.

Figure 5 | Outlet concentrations for main pollutants of concern from the four treatment technologies.
Total Kjeldahl nitrogen

There is only few data for TKN for FP, and they show low concentration percentage removal. Eight percent of AS samples present no removal of TKN, and outlet concentrations are the highest observed. Only 60% of the effluents are below 20 mg/L, in comparison to 75% for RBC, and more than 90% for F-VFTW. In addition, F-VFTW shows the best concentration percentage removal.

Ammonia

Again, ammonia is not systematically analyzed for FP, but it shows very good performances: 90% of the samples show more than 90% concentration percentage removal, with outlet concentrations below 10 mg/L. More than 10% of AS and RBC samples show no ammonia removal. Their patterns are close, even if RBC outlet concentrations are slightly better. F-VFTW shows better performances: 60% of the samples show over 80% removal, with outlet concentrations 75% below 10 mg/L (against 50–60% for AS and RBC).

Total phosphorus

None of these processes are designed to treat phosphorus. Except RBC performances, which are lower than the others, they follow the same pattern, which is fairly linear and mainly due to phosphorus assimilation by biomass.

Activated sludge

Even though AS is the most frequently implemented technology, the results show that it is the least reliable of the four technologies in this analysis. Approximately 17% of the sampling campaigns are below the minimum removal standards for TSS and COD and almost 50% of the BOD₅ outlet concentrations are above the discharge standards. This is mainly due to sludge leakage or washout during intense rain events, and is confirmed by the same observation for TSS in about 10% of the sampling campaigns. The loss of biomass during rain events as well as the lack of maintenance explains the absence of nitrification for about 12% of the campaigns.

Facultative ponds

FP shows very good concentration percentage removal for ammonia but not for TKN. This transfer from the mineral form of nitrogen to its organic form is probably the sign of algae production. The low concentration percentage removal for COD and TSS for about 10% of the campaigns tend to confirm this hypothesis. FP effluent often has high concentrations of suspended solids, mainly due to algae production (Mara & Pearson 1998). COD removal is better, with 93% of datapoints in compliance with minimum regulatory objectives. The low outlet concentrations associated with the low removal rate can be explained by the dilution of the influent wastewater, as the applied load in FP represents 10–15% of the nominal load (data not shown).

Rotating biological contactor

RBC presents the lowest compliance with effluent COD standards (82%). The performance in terms of concentration percentage removal are much better (close to 95%), but with only 87% of sampling campaigns meeting the TSS standard (Figure 4), sludge loss is suspected during the settling phase. Separation is a sensitive step for RBC during storm events, and subsequent sludge management during these events is a challenge. The performance of RBC is also limited regarding nitrification. As RBC is designed with or without nitrification objectives, it is not possible to comment on the overall process ability regarding ammonia or TKN removal.

French vertical flow treatment wetland

F-VFTW is the most reliable technology of the four technologies in this data analysis. It fulfills all the objectives at a frequency of 90–95%. The percentage removal rates below the minimum regulation for BOD₅/COD/TSS are, respectively, 5/9/3.1%. Regarding outlet concentrations, more than 90% of the samples meet the standard for COD. Performance for TKN is also very good (75% of reported values achieving greater than 70% TKN removal) whatever the specific design of treatment wetlands (one stage vertical filter unsaturated or saturated). This value is even slightly lower than what is reported for classical two-stage F-VFTW in temperate climates (Molle et al. 2005). F-VFTW in the FOT has only a single stage; as a result, complete nitrification is not expected.

Additional monitoring campaigns

Analysis of the data provided by the additional monitoring campaigns in terms of the French regulations is presented in Table 1. Percentage compliance with standards is on average lower for the additional monitoring campaigns than for those in the larger database. This could be explained by the
choice to focus on WWTPs below 1,000 PE for AS. As the regulatory monitoring frequency is lower for this range of capacity, they are under-represented in the larger database. In addition, for AS systems, the operator can usually choose the day for regulatory monitoring according to the climate, or repeat monitoring when a given sample does not comply with the standards. Such elements can contribute to the better performance observed in the larger database.

Previous conclusions of the analysis of the database were confirmed: sludge losses were observed for AS systems. RBC is more frequently associated with lamella plate settlement or rotary screens than with clarifiers. AS and RBC are generally chosen to keep the WWTP footprint as small as possible, but they require more maintenance or sludge emptying than clarifiers. Consequently, due to low maintenance, treatment performance is negatively affected.

The designs of the WWTPs in this study were state of the art, at least for temperate climates, except for FPs, for which an adaptation to tropical temperatures was taken into account. Very few data were available on maintenance. For five WWTPs, there were no maintenance reports or they were not updated frequently (>2 months). For two others, the operators visited the plant twice per month on average. Another WWTP was an AS of 200 PE, commissioned in 1998, which received two visits per week on average and showed a very good performance (>95% removal for BOD, TSS, >90% for COD, >70% for TKN, but with an average load of 50% of its nominal value). Due to the lack of information on sludge extraction, it was not possible to perform a mass balance on this system. Additional monitoring could have been interesting in order to explore its behavior during extreme rain events.

The number of samples for the additional monitoring of WWTPs was too small to draw broad conclusions, but the findings are consistent with the results for the larger database. Maintenance is a key parameter for explaining the performance of the treatment systems in the FOT. Each process has its own needs, but intensive treatment technologies require more attention than extensive processes. Sensitivity to hydraulic overloads is another important factor that was not investigated in this study but one that could be considered in future studies.

Comparison of treatment technologies based on the COR methodology

The COR methodology was used on the database values for the four technologies previously compared. In this study, we compare the design value obtained with the COR with the mean value from the database. The design concentration is the outlet concentration a plant is supposed to achieve on average, in order to reach the targeted standard with the level of reliability chosen according to the distribution of the data recorded. The discharge standards used are those defined by Oliveira & Von Sperling (2008) and are defined as a classical standard for developing countries: 60 mg/L BOD, 200 mg/L COD, 60 mg/L TSS and 20 mg/L TN. The results are presented in Table 2.

The COR analysis for the FOT dataset confirms that F-VFTW is the most reliable treatment process, as its observed concentrations are below (or close to) the design concentrations. This is not the case for the other treatment technologies, especially regarding TSS and TKN. Consequently, F-VFTW is the only treatment technology of the dataset that is able to achieve the discharge standard with a reliability of 95%.

While comparing the FOT dataset with values from Brazil (Oliveira & Von Sperling 2008), it is noticeable that both the design concentrations and the observed mean concentrations for AS are very close. It suggests that the two datasets are comparable, and that AS effluent concentrations follow the same distributions and produce the same level of effluent concentrations in Brazil and in the FOT. This is not the case for FP, probably due to the low load received by FP in the FOT. Also, pond systems are more sensitive to climate in terms of design and

<table>
<thead>
<tr>
<th>Compliance of the additional monitoring campaigns with the French regulatory objectives (%)</th>
<th>BOD</th>
<th>COD</th>
<th>TSS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 35 mg/L</td>
<td>&gt; 60% removal</td>
<td>&lt; 200 mg/L</td>
</tr>
<tr>
<td>4 AS (16)</td>
<td>73</td>
<td>100</td>
<td>73</td>
</tr>
<tr>
<td>2 RBC (8)</td>
<td>37</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>2 FP (8)</td>
<td>75</td>
<td>100</td>
<td>87</td>
</tr>
</tbody>
</table>

Total compliance is achieved if samples fulfill the regulatory objectives for all the parameters, in concentration percentage removal or in effluent concentration.
performance. It is likely that this impacts the COR analysis between Brazil and FOT. Considering the two datasets, F-VFTW remains the most reliable technology.

**CONCLUSIONS**

Comparison of treatment technology behaviors in real operating conditions shows that amongst the eight processes evaluated in FOT and Brazil, only the F-VFTW is able to achieve the discharge standard with a reliability of 95%. Performance assessment of the main technologies implemented in the FOT reveal important process failures for AS regarding sludge losses and nitrification. The settlement phase of RBC is identified as sensitive, affecting effluent concentrations for TSS and COD. FP performance is limited by algae growth, especially when the applied load is low.

In addition, this study highlights the weak operational and maintenance capacity in the FOT. This could partly explain the low reliability of intensive treatment processes such as AS or RBC compared to more extensive ones (FP or F-VFTW) which requires less complex and less frequent operation and maintenance tasks. Nevertheless, sensitivity to hydraulic overloads related to tropical rain is also suggested, in addition to breakouts and maintenance limitations. For small communities (<2,000 PE) in the FOT, and amongst the treatment process studied, the F-VFTW appears to be the technology most suited to both environmental (rainfall patterns) and social (low maintenance capacities) constraints.

**ACKNOWLEDGEMENTS**

The authors thank the French Agency for Biodiversity for its financial support, the local water authorities (Office de l’Eau de la Martinique, de la Guadeloupe, de la Guyane, de la Réunion, le Syndicat Mixte des Eaux et de l’Assainissement de Mayotte) and the French Ministry for the Ecological and Solidary Transition for providing data. Special thanks to Jaime Nivala for her careful review.

**DATA AVAILABILITY STATEMENT**

Data cannot be made publicly available; readers should contact the corresponding author for details.

**REFERENCES**


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**Table 2** Mean design concentrations (DC) to achieve 95% compliance with the standards and mean observed concentrations (OC), in the FOT and Brazil (Oliveira & Von Sperling 2008)

<table>
<thead>
<tr>
<th>Type of treatment plant (n)</th>
<th>BOD (mg/L)</th>
<th>COD (mg/L)</th>
<th>TSS (mg/L)</th>
<th>TN (mg/L)</th>
<th>TKN (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DC</td>
<td>OC</td>
<td>DC</td>
<td>OC</td>
<td>DC</td>
</tr>
<tr>
<td>FOT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AS (147)</td>
<td>25</td>
<td>37</td>
<td>100</td>
<td>129</td>
<td>25</td>
</tr>
<tr>
<td>RBC (32)</td>
<td>26</td>
<td>41</td>
<td>102</td>
<td>101</td>
<td>24</td>
</tr>
<tr>
<td>FP (12)</td>
<td>30</td>
<td>12</td>
<td>111</td>
<td>85</td>
<td>25</td>
</tr>
<tr>
<td>F-VFTW (10)</td>
<td>27</td>
<td>15</td>
<td>112</td>
<td>68</td>
<td>24</td>
</tr>
<tr>
<td>Brazil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ST + AF (19)</td>
<td>29</td>
<td>292</td>
<td>104</td>
<td>750</td>
<td>29</td>
</tr>
<tr>
<td>FP (73)</td>
<td>30</td>
<td>136</td>
<td>127</td>
<td>525</td>
<td>31</td>
</tr>
<tr>
<td>AP + FP (43)</td>
<td>98</td>
<td>89</td>
<td>127</td>
<td>309</td>
<td>34</td>
</tr>
<tr>
<td>AS (13)</td>
<td>24</td>
<td>35</td>
<td>85</td>
<td>92</td>
<td>23</td>
</tr>
<tr>
<td>UASB (10)</td>
<td>30</td>
<td>98</td>
<td>107</td>
<td>251</td>
<td>26</td>
</tr>
<tr>
<td>USAB + POST (8)</td>
<td>27</td>
<td>42</td>
<td>98</td>
<td>141</td>
<td>26</td>
</tr>
</tbody>
</table>

(n) number of WWTP evaluated. ST + AF: septic tank + anaerobic filter; AP + FP: anaerobic ponds + facultative ponds; UASB: upflow anaerobic sludge blanket reactor; UASB + POST: UASB reactor + several post treatment.
Performance of a single stage vertical flow constructed wetland system treating raw domestic sewage in Brazil. *Water Science and Technology* 68 (7), 1599–1606.


First received 29 April 2020; accepted in revised form 3 September 2020. Available online 17 September 2020