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Treatment performances of French constructed wetlands: results from a database collected over the last 30 years

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ABSTRACT

Approximately 3,500 constructed wetlands (CWs) provide raw wastewater treatment in France for small communities (<5,000 people equivalent). Built during the past 30 years, most consist of two vertical flow constructed wetlands (VFCWs) in series (stages). Many configurations exist, with systems associated with horizontal flow filters or waste stabilization ponds, vertical flow with recirculation, partially saturated systems, etc. A database analyzed 10 years earlier on the classical French system summarized the global performances data. This paper provides a similar analysis of performance data from 415 full-scale two-stage VFCWs from an improved database expanded by monitoring data available from Irstea and the French technical department. Trends presented in the first study are confirmed, exhibiting high chemical oxygen demand (COD), total suspended solids (TSS) and total Kjeldahl nitrogen (TKN) removal rates (87%, 93% and 84%, respectively). Typical concentrations at the second-stage outlet are 74 mgCOD L^{-1}, 17 mgTSS L^{-1} and 11 mgTKN L^{-1}. Pollutant removal performances are summarized in relation to the loads applied at the first treatment stage. While COD and TSS removal rates remain stable over the range of applied loads, the spreading of TKN removal rates increases as applied loads increase.

Key words | database, French system, treatment performances, vertical flow constructed wetland

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INTRODUCTION

Constructed wetlands (CWs) have been proven to be effective and offer an attractive and sustainable alternative for wastewater treatment technology for small communities (<5,000 people equivalent, p.e.). The simplicity of operation, maintenance and the low-operating costs are suited to the limited resources that small communities are able to dedicate to wastewater treatment. Moreover, CWs have a high capacity for buffering hydraulic and organic load fluctuations as well as high resilience.

After 30 years of development of CWs treating domestic wastewater for small communities in France, about 3,500 plants are currently in operation. Most of them are composed of two stages of vertical flow constructed wetlands (VFCWs) in series, but many configurations exist (association with horizontal flow, pond systems or conventional treatment systems, one stage of vertical flow with recirculation, partially saturated systems, etc.) (Aguilera Soriano *et al.* 2011; Prost-Boucle & Molle 2012; Kim *et al.* 2014). Current practice usually involves two treatment stages, with three units in parallel in the first stage and two for the second, with successive periods of feeding (3.5 days), and rest periods (7 days at the first stage and 3.5 at the second stage) to maintain permeability, oxygen content and to control biomass growth (Liénard *et al.* 1990a, b). VFCWs are appropriate when the nitrogen forms contained in wastewater have to be nitrified. A previous database analysis was carried out 10 years ago on the classical French system (two stages of VFCW in series), allowing the global performances to be observed (Molle *et al.* 2005). Regarding the French regulation for plants with a capacity between 200 and 2,000 p.e. (minimum chemical oxygen demand (COD), biochemical oxygen demand (BOD_5) and total suspended solids (TSS) removal efficiencies of 60%, 60% and 50%, respectively, or maximum effluent concentration of 35 mgBOD_5 L^{-1}, are allowed), this system achieves very good pollutant removal efficiencies; it has an overall filtration surface for both stages of 2 m^2 p.e.$^{-1}$: >90% for COD, 95% for TSS and 85% for total Kjeldahl nitrogen removal (TKN), in spite of fluctuations in organic and hydraulic loads, and 60 mgCOD L^{-1}, 15 mgTSS L^{-1} and 8 mgTKN L^{-1} as average concentrations at the outlet of the system.

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If we focus on the first stage of VFCW, its design is based on an acceptable organic load, often expressed as a filter surface unit per p.e. Generally, the organic designed load applied to the filter in operation is 300 gCOD $m^{-2} d^{-1}$, 150 gTSS $m^{-2} d^{-1}$ and 25–30 gTKN $m^{-2} d^{-1}$; the hydraulic load is 0.37 m d^{-1}. The originality of this stage lies mainly in the fact that it is fed with raw wastewater (and therefore the development of a sludge layer over the years) as well as being filled with a coarse granular media. Molle *et al.* (2005) pointed out that with a first-stage surface of 1.2 m^2 p.e.$^{-1}$, it achieves a COD and TSS removal of 79% and 86%, respectively, while nitrification is incomplete at 50–60% of inlet TKN.

This study provides an assessment of the overall reliability of the French system, particularly the first stage of VFCW, in order to make a more extensive database than the one used by Molle *et al.* (2005). We collected and summarized information about the design and operating parameters of some of the two stages of VFCW currently in operation. This paper gives an overview of the number of plants, their design and their efficiency.

MATERIALS AND METHODS

Data collection

Currently, around 3,500 CW plants are in operation in France. The data collection aimed to gather all possible information on existing CWs in France: the type of filters, the altitude of the CWs, the commissioning date, feeding and drainage systems, and also filters' characteristics (e.g., the number of filters in operation, filter dimensions, particle sizes, etc.). The database achieved consisted of about 700 CW plants with different configurations (association between VFCW and HFCW or waste stabilization pond systems, VFCW with recirculation, partially saturated systems, etc.). Among them, 67% are two stages of VFCW in series and 6% have only one stage of VFCW. Thus, a sample of 415 VFCW plants was selected to assess treatment performances with 24 h-flow proportional composite samples taken from the inlet and the outlet of the CWs (carried out by the French technical department (SATESE) and Irstea). These 24 h-flow proportional composite samples included measurements of COD, BOD_5, TSS, TKN, ammonia-nitrogen (NH_4N), nitrites (NO_2N), nitrates (NO_3N), phosphate phosphorus (PO_4P), total phosphate (TP), pH and conductivity, when they were measured, according to APHA (2012).

In this study, we focused on the classic French system: two stages of VFCW. Once the design characteristics and the 24 h-flow proportional composite samples related to this configuration were compiled in the database, a validation step for these composite samples from the inlet of the first stage of VFCW was performed. This approach was intended to remove 24 h-flow proportional composite samples with inconsistent results or that were considered outliers. Consistency was verified by calculating the following ratios between the different inlet pollutant concentrations as COD/BOD_5, TKN/COD, TP/COD, TSS/COD,BOD_5/TKN, BOD_5/TKN and NH_4N/TKN and comparing them to domestic wastewater values (Table 1) defined from a previous study about domestic wastewater characteristics in French rural areas (<2,000 p.e.) (Mercoiret *et al.* 2010).

The removal efficiencies of the whole system and of each stage were calculated in %, while applied and treated loads of pollutants were expressed in terms of g $m^{-2} d^{-1}$.

RESULTS

General description of the database

Among the information collected for the 415 VFCW plants selected in the database we note the following:

- Among the two-stage VFCW plants with available data, the average dimensions of the whole system is 2 m^2 p.e.$^{-1}$, divided between the first stage (mean: 1.2 m^2 p.e.$^{-1}$; min: 0.2 m^2 p.e.$^{-1}$; max: 3.8 m^2 p.e.$^{-1}$; number of values: 136), and the second stage (mean: 0.8 m^2 p.e.$^{-1}$; min: 0.1 m^2 p.e.$^{-1}$; max: 2.7 m^2 p.e.$^{-1}$; number of values: 133).
- The filtering material average depth of the first stage is 53 cm (SD: 14 cm; $N = 73$).

Table 1 | Domestic wastewater characteristics in French rural areas (Mercoiret *et al.* 2010)

		COD/BOD_5	TKN/COD	TP/COD	TSS/COD	BOD_5/TKN	BOD_5/TP	NH_4N/TKN
Mean		2.62	0.12	0.02	0.46	3.88	28.53	0.74
Range of variations	Upper bound	3.93	0.18	0.03	0.79	6.50	47.01	0.97
	Lower bound	1.83	0.06	0.01	0.23	1.90	12.60	0.50
Number of values		10,275	9,416	9,184	10,256	9,416	9,184	4,244

- The filtration layer of the second stage is composed of sand and fine gravel stacked layers. The average depths are 44 cm (SD: 20 cm; $N = 106$) for sand and 26 cm (SD: 10 cm; $N = 64$) for fine gravel.
- The average plant capacity is 469 p.e. (median 330 p.e.), and 43% of the 415 VFCW plants have a nominal capacity of less than 250 p.e. (see Figure 1, left).
- The age of the plants ranges from 2 years for the most recent VFCW plant and 31 years for the oldest (mean and median: 10 years and 9 years, respectively). Fifty-five percent of the plants are between 7 and 11 years old (see Figure 1, right).
- Seventy-seven percent of the VFCW plants only treat domestic wastewater and 78% of the VFCW are connected to a separate sewer system.
- The feeding system is mostly gravity-type (when the information was available, we observed that 72 and 88% of the first and the second stage of VFCW, respectively, were fed without energy supply).

Currently, the database contains 964 24 h-flow proportional composite samples from all available configurations listed in the database. Among these 24 h-flow proportional composite samples, 535 correspond to the two-stage VFCW configuration and 259 correspond to the output of the first VFCW stage.

Figure 2 presents the dispersion of COD, BOD_5, TSS (left) and TKN (right) concentrations measured in the raw wastewater.

Mean and median concentration values are close for all parameters (COD, BOD_5, TSS and TKN). In this sample, 90% of COD, BOD_5, TSS and TKN concentrations are below 1,036 mg L^{-1}, 484 mg L^{-1}, 508 mg L^{-1} and 110 mg L^{-1}, respectively. The calculated values for this sample of two-stage VFCW plants are similar to those obtained by Mercoiret et al. (2010) (COD: mean = 646 mg L^{-1}, SD = 395 mg L^{-1}; BOD_5: mean = 265 mg L^{-1}, SD = 171 mg L^{-1}; TSS: mean = 288 mg L^{-1}, SD = 226 mg L^{-1}; TKN: mean = 67 mg L^{-1}, SD = 35 mg L^{-1}).

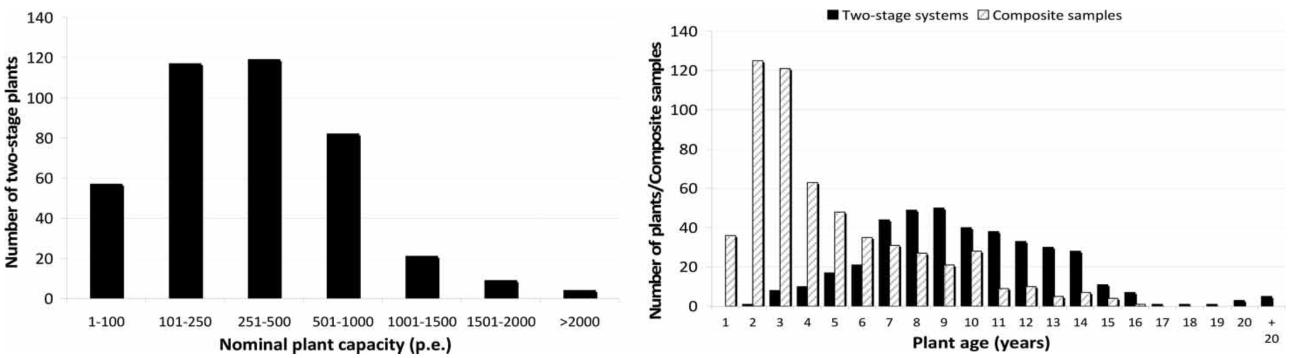

Figure 1 | Distribution of the number of two-stage systems according to nominal plant capacity (left). Distribution of the number of composite samples and the number of two-stage systems according to plant age (right).

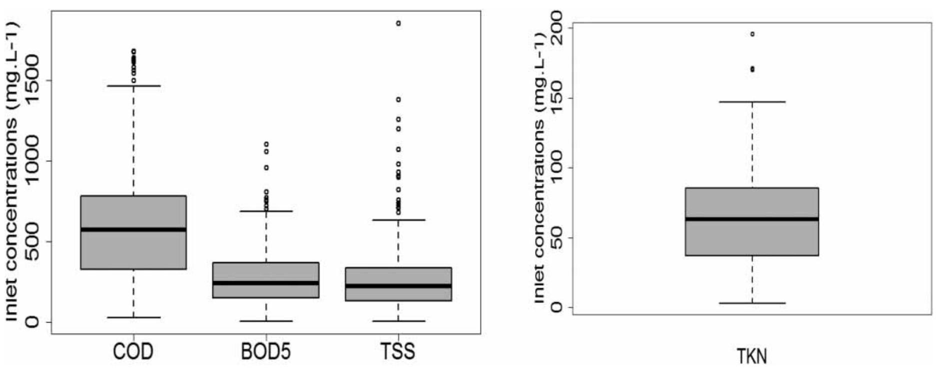

Figure 2 | Raw wastewater concentrations (COD, BOD_5 and TSS on the left; TKN on the right) applied to the two-stage VFCW system. $N = 394$, $N = 386$, $N = 397$ and $N = 325$ for COD, BOD_5, TSS and TKN, respectively. N: the number of values.

The two-stage VFCW

Among all the plants identified in the database, the two-stage VFCWs represent 380 plants. Moreover, 422 composite samples are available from 119 different two-stage plants. Generally, the plants feature hydraulic and organic loads of about 94% and 54%, respectively, with large variations on the first stage in operation (hydraulic load: mean = 0.37 m d^{-1}, SD = 0.39 m d^{-1}, min–max = 0.05–2.20 m d^{-1}; organic load: mean = 161 mgCOD m^{-2} d^{-1}, SD = 104 mgCOD m^{-2} d^{-1}, min–max = 12–557 mgCOD m^{-2} d^{-1}).

Figure 3 presents the cumulative percentages for the COD, BOD_5, TSS and TKN concentrations measured in the wastewater in both the first-stage and second-stage outlets.

While the wastewater concentrations are spread over a wide range of values, the concentration distributions at the second-stage outlet are much denser and concentrations are low. This densification of the outlet concentrations is less apparent for TKN with a greater spread of values (min–max: 1–93 mg L^{-1}). For the four parameters represented in Figure 3, the 90% of COD, BOD_5, TSS and TKN concentrations are below 95 mg L^{-1}, 22 mg L^{-1}, 25 mg L^{-1} and 26 mg L^{-1}, respectively.

Table 2 presents the average outlet concentrations and removal efficiencies for COD, TSS and TKN calculated for the global system. Removal efficiencies are 87%, 93% and 84% for COD, TSS and TKN, respectively. These values are consistent with those calculated by Molle et al. (2005) (91%, 95% and 85% for COD, TSS and TKN, respectively) even if the plants are older on average (55% of the plants are between 7 and 11 years old, whereas most of the plants were 4–6 years old in Molle et al. (2005)) and the number of values is larger. The scatter of the outlet concentrations is greater than for the removal efficiencies, even if the classic outlet requirements are respected (125 mgCOD L^{-1}, 35 mgTSS L^{-1} and 25 mgBOD_5 L^{-1}) even for pollutant loads up to 2–5 times the nominal load. These concentrations depend on characteristics relating to design (filter surface, height of filter material) and operating (hydraulic loads). Therefore, the classical French system is still an efficient and robust method for treating wastewater from small communities.

Nevertheless, the overall efficiencies do not fully reflect the efficiency of each stage. Indeed, if one of the two stages fails to treat the pollutants, the other can compensate for this dysfunction and smooth the removal efficiencies. It is

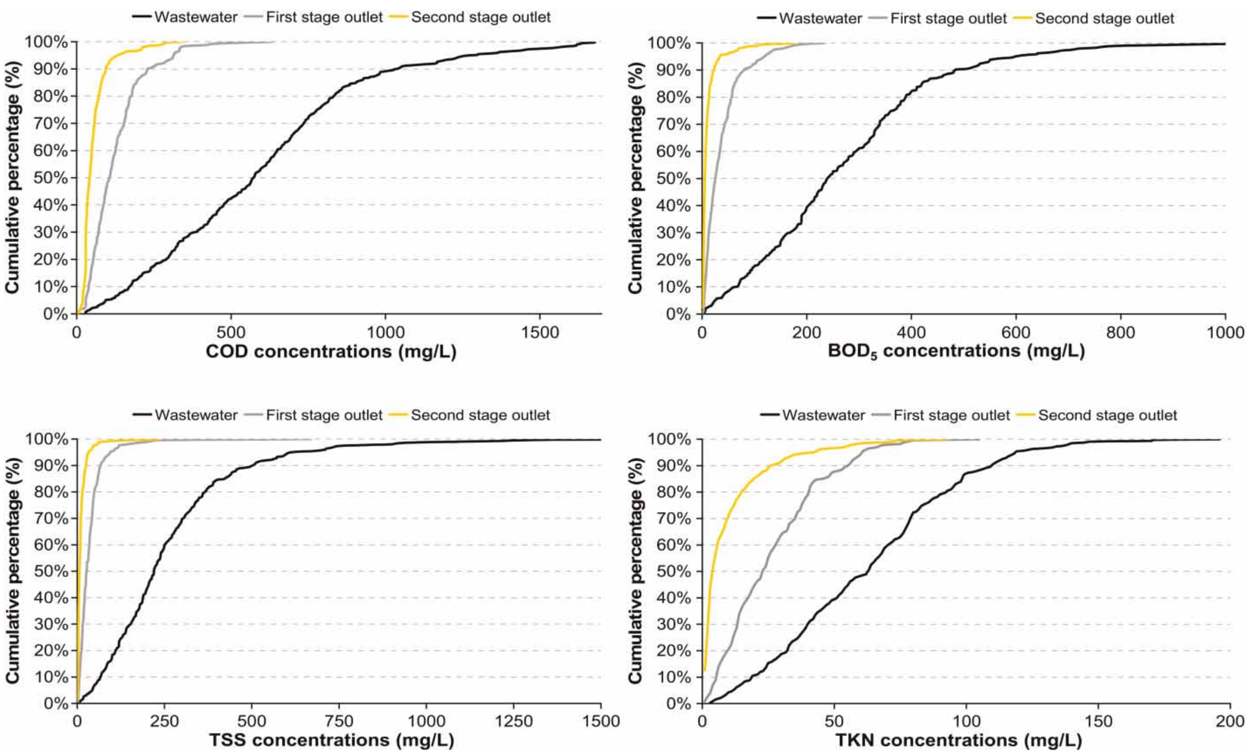

Figure 3 | COD (top left), BOD_5 (top right), TSS (bottom left) and TKN (bottom right) concentrations for the wastewater ($N = 394$, $N = 386$, $N = 397$, $N = 325$ for COD, BOD_5, TSS and TKN, respectively), the first-stage outlet ($N = 250$, $N = 243$, $N = 252$, $N = 228$ for COD, BOD_5, TSS and TKN, respectively) and the second-stage outlet ($N = 395$, $N = 388$, $N = 397$, $N = 344$ for COD, BOD_5, TSS and TKN, respectively).

Table 2 | Effluent pollutant concentrations and removal efficiencies from the two-stage VFCW system

	COD		TSS		TKN	
	Outlet concentration (mg L^{-1})	Removal efficiency (%)	Outlet concentration (mg L^{-1})	Removal efficiency (%)	Outlet concentration (mg L^{-1})	Removal efficiency (%)
Mean ± X (*N*) SD	74 ± 16 (417) 168	87 ± 2 (409) 14	17 ± 6 (418) 64	93 ± 1 (411) 9	11 ± 2 (357) 13	84 ± 2 (329) 17
Molle *et al.* (2005)	66 ± 13 (49) 46	91 ± 3 (49) 46	14 ± 5 (49) 18	95 ± 2 (49) 18	13 ± 5 (49) 18	85 ± 5 (49) 17

SD: standard deviation; *N*: the number of values; $\pm X = 1.96*(SD/\sqrt{N})$: 95% confidence interval.

often the first stage that faces some difficulties in treating TKN and the second stage that compensates for low TKN removal efficiencies. That is why we focus on the treatment effectiveness of the first stage.

Focus on the first stage of VFCW

Among all the plants identified in the database, the data (including measurement at the outlet of the first stage) concern 51 plants for a total of 252 composite samples.

As for the second stage, the concentration distributions at the first-stage outlet (see Figure 3) are also denser compared to the wastewater concentration distributions for COD, BOD_5, TSS and TKN (but less dense than the distributions at the second stage). In addition, TKN concentrations present a larger range of values, from 1 mg L^{-1} to 105 mg L^{-1}, than COD, BOD_5 and TSS; 90% of COD, BOD_5, TSS and TKN concentrations are below 230 mg L^{-1}, 80 mg L^{-1}, 67 mg L^{-1} and 55 mg L^{-1}, respectively.

Table 3 presents the average outlet concentrations and removal efficiencies for COD, TSS and TKN calculated for the first stage of treatment. These values confirm that the main roles of this treatment stage are TSS retention (removal efficiency of 83%) as well as degradation of part of the COD (removal efficiency of 77%), as found in Molle *et al.* (2005). The stability of COD and TSS removal efficiencies is clear in Figure 4 (left). Figure 4 displays the removal efficiencies for COD, TSS and TKN relating to their respective loads applied at the first stage (the dashed line represents 100% removal). Despite the high loads applied at the first stage (up to 2 and 6 times the nominal load for COD and TSS, respectively), the removal efficiencies for COD and TSS are satisfactory with removal efficiencies greater than 80% and 91%, respectively. It highlights the robustness of the system, i.e., how it can accept occasional overloads without affecting removal rates.

For this treatment stage, TKN removal efficiency is less important (60%, 58% in Molle *et al.* (2005)) than that of COD and TSS. As expected, treatment performances decrease while the load increases. This has already been observed by previous studies (Molle *et al.* 2005, 2008) and reflects the limits the filter can reach in terms of oxygen renewal, hydraulic shortcuts and ammonium adsorption.

Nevertheless, Figure 4 (right) shows a wide dispersion of the values even for loads under the designed load (25–30 gTKN m^{-2} d^{-1}). The fitting curve from Molle *et al.* (2008) (Figure 4, left) was obtained with a filter of 80 cm made of gravel with intermediate aeration and good distribution of effluent on the filter. It can be considered as a reference curve since no dispersion on the nitrification rate was measured, whatever the season and temperature. In comparison with TKN loads from Molle *et al.* (2008), the values from this study are widely scattered around the curve. This highlights the greater sensitivity of the

Table 3 | Effluent pollutant concentrations from the first stage of VFCW

	COD		TSS		TKN	
	Outlet concentration (mg/L)	Removal efficiency (%)	Outlet concentration (mg/L)	Removal efficiency (%)	Outlet concentration (mg/L)	Removal efficiency (%)
Mean ± X (*N*) SD	126 ± 11 (250) 90	77 ± 2 (250) 14	38 ± 4 (252) 33	83 ± 2 (252) 15	27 ± 2 (228) 19	59 ± 3 (223) 21
Molle *et al.* (2005)	131 ± 20 (54) 71	79 ± 3 (54) 10	33 ± 6 (54) 19	86 ± 3 (54) 19	31 ± 5 (54) 17	58 ± 5 (54) 17

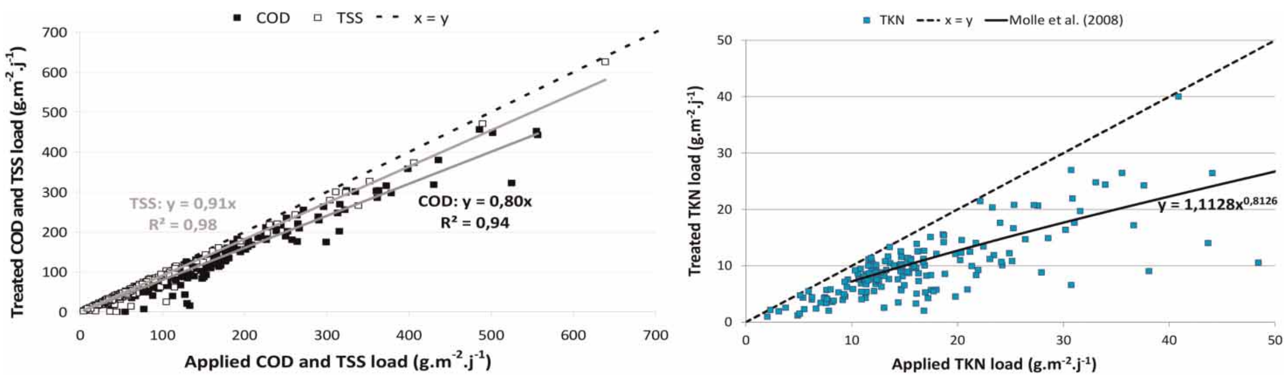

Figure 4 | Treated COD, TSS (left) and TKN (right) loads according to the COD, TSS and TKN loads applied to the first stage of VFCW system. $N = 190$ for COD and TSS loads; $N = 174$ for TKN loads.

nitrification process to design and operating conditions. Many parameters can impact the nitrification rate, such as design parameters (depth of material, particle size of the media, batch feeding system, including distribution pipes, and drainage pipes), as well as external factors (age of the filter, temperature, hydraulic load (storm event and clear water intrusion)), and operating parameters (alternation of filters and day of feeding) (Taniguchi *et al.* 2009; Stefanakis & Tsihrintzis 2012). This graphical representation is not sufficient for involving one or more specific design and/or operation characteristics to explain the dispersions observed around the general trend shown in Figure 4 (right). They certainly result from one of, or the combination of, several parameters.

This database currently lacks precise design information considering depth and particle size of the filtering media, as well as in terms of maintenance quality. Thus, it has not been possible to point out the main parameters that impact on the nitrification process. Neither the hydraulic load alone, nor the age of the filter (Figure 5) explain this dispersion. Whatever the age of the plants at which the 24 h-flow proportional composite samples is carried out, the treated TKN load is satisfactory. This does not mean that nitrification varies in unpredictable ways, but that the database needs to be more informed on design parameters. Indeed, when Molle *et al.* (2008) worked on one single filter, they measured no dispersion on nitrification rate, whatever the season and temperature. This stability might be linked to the depth of the filters used (60 and 80 cm filtration layer) and the particle size of 2–4 mm. Indeed, it is in accordance with trend towards modifying the French guidelines to narrow the particle size distribution from 4–8 to 2–6 mm and even 2–4 mm. In addition, when nitrification requirements are stringent, using 60 cm of gravel is recommended for a single VFCW plant.

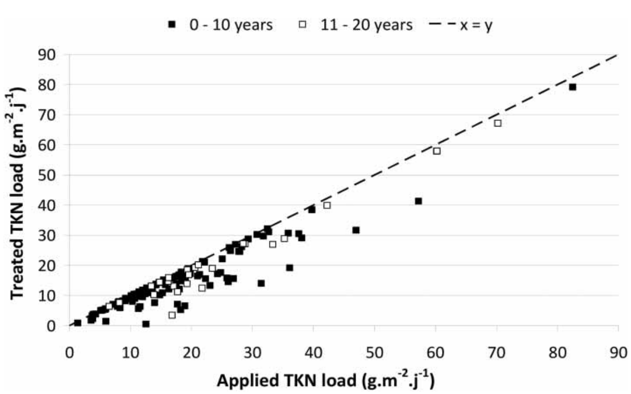

Figure 5 | Treated TKN loads according to the TKN loads applied to the first stage of old VFCW plants (aged from 13 to 20 years) according to the age of the plants when the composite samples were made. $N = 131$.

CONCLUSION

This study reviewed the performance of the two-stage VFCW in series and the first stage of VFCWs alone, all of them fed with raw wastewater. It was confirmed that the two-stage configuration is robust and suitable for the treatment of raw sewage. Moreover, we state the following:

- Performances observed in this study are consistent with previous data sets. Over a wide range of plants aged from 2 to 31 years (mean of 10 years), concentrations measured at the outlet of the second stage and removal efficiencies are substantially close to the previous study conducted 10 years earlier on the same configuration: 74 mgCOD L^{-1} (COD removal efficiency of 87%), 17 mgTSS L^{-1} (TSS removal efficiency of 93%) and 11 mgTKN L^{-1} (TKN removal efficiency of 84%).

- Robust performances for TSS and COD for the first stage. Values confirm that the main roles of the first treatment stage are TSS retention (removal efficiency of 83%) as well as degradation of part of the COD (removal efficiency of 77%).
- Good but variable performance for TKN for the first stage. There is a large dispersion of the treated TKN load values according to the TKN load applied. Owing to the lack of information relating to the design parameters or operating conditions of the plants, no characteristics have been highlighted for demonstrating effects on the nitrification process.

A statistical study is currently underway, which aims to explain the variations in TKN removal efficiencies observed in the first stage. This effort entails filling in the missing data in the database, and resampling values to avoid bias and to better decompose the variance.

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