

# Performance of the first stage of the French system of vertical flow constructed wetlands with only two units in parallel: influence of pulse time and instantaneous hydraulic loading rate

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## ABSTRACT

The technology of vertical flow constructed wetlands – French system for treating raw wastewater depends on several hydraulic factors, one of them being the duration of the pulse feeding and the resulting instantaneous hydraulic loading rate. This paper analyses two scenarios in the same system, the first of a faster feeding by pump and the second of a slower feeding by siphon, both with instantaneous hydraulic loading rate values lower than the literature recommendations. The system treated raw wastewater from a population equivalent of 100 p.e. in Brazil, and was comprised by only the first stage and two units in parallel. The shorter duration of feeding time and higher instantaneous hydraulic loading rate were associated with significantly higher chemical oxygen demand and total Kjeldahl nitrogen removal efficiencies, but with no significant differences in terms of biochemical oxygen demand (BOD) and suspended solids (SS). Oxygen concentrations and redox potential in the effluent were evaluated, together with the effluent flow rate profiles. The removal efficiencies were associated with the accumulation of solids in the upper part of the filter resulting from seven years of operation and to the operating hydraulic conditions, which are important elements in the performance of the system.

**Key words** | effluent flow rates, feeding by pump, feeding by siphon, pulse loading

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## INTRODUCTION

Constructed wetlands (CWs) have been proven to be effective and to offer an attractive and sustainable alternative for wastewater treatment for small communities (<5.000 population equivalents, p.e.) (Troesch *et al.* 2014). 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 having a high resilience to environmental and operational variabilities (Morvannou *et al.* 2015).

Vertical flow systems with intermittent feeding represent an important variant of subsurface flow constructed wetlands. These systems can fulfil stringent effluent standards and guarantee low effluent concentrations, as shown by extensive surveys carried out by Molle *et al.* (2005) and Morvannou *et al.* (2015) on the French version of vertical flow constructed wetlands (VFCWs), in which the following

mean effluent concentrations have been obtained in the two surveys: chemical oxygen demand (COD): 66 and 74 mg L<sup>-1</sup>, total Kjeldahl nitrogen (TKN): 13 and 11 mg L<sup>-1</sup>, and total suspended solids (TSS): 14 and 17 mg L<sup>-1</sup>. When considering the difficulties of developing countries for implementing and maintaining wastewater treatment systems, with a large number of treatment plants with different processes performing poorly or having even been abandoned, the possibility of applying such a simple system in thousands of small communities, with good removal efficiencies and simple operation, is a matter of great relevance.

Analysing a more specific aspect, VFCWs are extremely reliant on aerobic processes; clogging of the substrate matrix critically hinders the oxygen transport and therefore results in a rapid failure of the treatment performance of the system (Langergraber *et al.* 2003). The challenge is to keep aerobic conditions in the filter but without oversizing the system.

Focusing on the oxygen demand and the oxygen supply of a system (as is usually done in the design of most technical treatment plants) seems to be a coherent approach. The major air transport mechanisms into the filter bed are diffusion and convection. Convection is the transport of oxygen into the filter induced by the water flow. Depending on the hydraulic behaviour of the filter, the whole or only parts of the effluent water volume are replaced by air from the atmosphere. Regarding the diffusion process, it has to be emphasized that the oxygen transport by diffusion in water is much slower than in air. Therefore, the oxygen transport by diffusion strongly depends on the current water/air content in the pores. Related to this, the clogging process of a filter usually appears simultaneously with a decreasing rate of infiltration (Kaysner & Kunst 2005).

For systems treating raw wastewater, each stage of VFCWs usually comprises several filters in parallel. In the French version of vertical wetlands, it usually involves two treatment stages, with three units in parallel in the first stage and two in the second, with successive periods of feeding (usually 3.5 days) and resting periods (7 days at the first stage and 3.5 at the second stage) to maintain permeability and oxygen content and to control biomass growth (Morvannou *et al.* 2015). This alternation between feeding and resting periods has two major purposes: (1) degradation of the particulate organic matter and (2) control of bacterial growth in order to limit biological clogging issues (Petitjean *et al.* 2011).

The hydraulic and organic loads as well as the operating conditions (batch feeding, alternation between feeding and resting periods) have to be well controlled to favour mineralization of the top deposit layer. If not, the deposit layer can induce process limitations such as excessive ponding at the surface, oxygen transfer limitation (convection and diffusion) and decreasing biosolids mineralization. If the formation of a deposit layer is necessary in the French system, equilibrium has to be maintained so as not to reach a degree of clogging at which performance, robustness, reliability and durability of the unit are affected. Furthermore, the deposit layer accumulated on the surface of the system seems to play an important role in wastewater retention, as well as in the biological system profile, associated with the microbiological diversity, improving VFCW treatment efficiency (Molle 2014).

For the design of VFCW, hydraulic aspects play an important role that may influence oxygen transfer to the bed. Some of these aspects are associated with the input of wastewater on to the system: (i) batch frequency, (ii) feeding time during the pulse, (iii) instantaneous hydraulic loading

rate and (iv) density of distribution points over the filter surface.

The batch frequency, and hence the wastewater volume to be applied at each batch, is recommended to lead to a thickness between 2 and 5 cm of liquid on top of the filter surface to ensure adequate distribution of liquid on the whole surface and to allow the visualization of this distribution. Liquid levels below 2 cm are hard to visualize and are indicative of possible uneven distribution on the surface, and values above 5 cm may be indicative of the risk of preferential flow (short-circuiting). For design purposes, after specifying the desired water level that will cover the filter during each batch ( $\text{m batch}^{-1}$ ), one can determine the volume per batch ( $\text{m}^3 \text{batch}^{-1}$ ) by multiplying the filter surface area ( $\text{m}^2$ ) by this water level ( $\text{m batch}^{-1}$ ). The number of batches per day ( $\text{batch d}^{-1}$ ) is determined by the division between the daily flow ( $\text{m}^3 \text{d}^{-1}$ ) and the calculated volume per batch ( $\text{m}^3 \text{batch}^{-1}$ ) (Dotro *et al.* 2017). Batch frequency also has implications in terms of oxygen transfer. More batches per day, with lower volumes in each batch, may favour organic matter removal, while the opposite, with less batches per day, with higher volumes per batch, may induce a higher suction of air following the liquid percolation, which may assist in enhancing aerobic conditions within the bed and, thus, possibly improving nitrification (Molle *et al.* 2006). These guidelines have been developed based on the experience on temperate climates. In warm climate regions, it is important to take into account the storage time in the accumulation box: low batch frequencies, which are associated with long retention (several hours) of raw wastewater in the accumulation box, may lead to anaerobic decomposition in the box, with possible release of malodours resulting from the fast reactions taking place in warm climates.

The feeding time during the pulse is in the order of a few minutes and is related to the instantaneous hydraulic loading rate during the pulse, which will dictate the flow rate during feeding. With the volume to be fed at each batch and the flow rate to be used, the pulse duration is calculated (Dotro *et al.* 2017).

The instantaneous surface hydraulic loading rate is recommended to be higher than  $0.5 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$  ( $8 \text{ L m}^{-2} \text{ min}^{-1}$ ) (Dotro *et al.* 2017) or  $0.6 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$  ( $10 \text{ L m}^{-2} \text{ min}^{-1}$ ) (Molle *et al.* 2005). It is possible that a short feeding time and a high instantaneous flow could positively influence the performance of the system. This phenomenon would affect the VFCW hydrodynamics and the transfer of oxygen to the system due to the rupture of the constructed wetlands balance between the several factors

involved in the filtration efficiency, the water contact time with the filter material and the removal of contaminants. In warm climate regions it is important to investigate whether these minimum recommended values of  $0.5 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$  (Dotro *et al.* 2017) or  $0.6 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$  (Molle *et al.* 2005) are applicable, or if lower values (which facilitate feeding and reduce pump requirements) may be used.

Regarding the density of influent distribution points on the filter surface, the recommendation for the first stage of the French system is of one feeding point per  $50 \text{ m}^2$  (Dotro *et al.* 2017). This is to ensure adequate distribution across the whole filter surface, thus avoiding zones with excessive or insufficient supply of wastewater.

Concerning the number of units and land requirements in the first stage of VFCW, one of the possibilities is that in warm climate regions the area of the treatment units can be smaller compared with those in cold climates (Kantawanichkul *et al.* 2009; Lana *et al.* 2013; Molle *et al.* 2015). Also, in warm climate regions it is expected that most conversion processes can take place in the first stage. This brings about considerable land and construction cost savings. Nowadays, research has been conducted in order to find out appropriate operation conditions that allow satisfactory performance of the system (Cota *et al.* 2011; Manjate *et al.* 2015).

Molle (2012) reinforces the need for seeking different configurations of the French system in order to further reduce costs. If only the first stage is adopted, total land requirements are only 60% of those needed for a two-stage system, but the final effluent is likely to have a poorer quality, depending on local climate and wastewater characteristics. Additional savings could be achieved by having only two units in the first stage, instead of three, leading to a total land requirement of only around 40% of the original system, as investigated by Lana *et al.* (2013) and Manjate *et al.* (2015) in Brazil. In their studies, with only the first stage in the system, and with only two units in the first stage, the land requirements were only  $0.6 \text{ m}^2$  population equivalent<sup>-1</sup>, much lower than the typical value of  $2.0 \text{ m}^2$  population equivalent<sup>-1</sup> applied in France, for a two-stage system with all units. In the experiments of Manjate *et al.* (2015), the following mean removal efficiencies have been obtained when operating with three and two units in parallel in the first stage (no second stage was used): 81% and 59% for COD, 82% and 74% for biochemical oxygen demand (BOD), 85% and 67% for TSS and 56% and 49% for TKN, respectively. Therefore, a certain decrease in terms of the system performance took place when the number of units and the total surface area was

reduced, and it is a matter of the interpretation of the local regulations to decide whether such a reduction in the removal efficiency is still acceptable.

An overall evaluation of the previous results obtained by Lana *et al.* (2013) and Manjate *et al.* (2015), which counted with the favourable climatic conditions of a tropical environment (Brazil), was that the removal efficiencies obtained when the system operated in a similar fashion to the French recommendations (three units in the first stage) were somewhat similar to those obtained in France, such as those reported by Morvannou *et al.* (2015). In France, systems are designed for a per capita BOD load of  $60 \text{ g p.e}^{-1} \text{ d}^{-1}$  (Dotro *et al.* 2017), while in Brazil, for instance, lower values are usually adopted (around  $50 \text{ g p.e}^{-1} \text{ d}^{-1}$ ). Also, TKN concentrations in Brazil tend to be lower than the values reported by Morvannou *et al.* (2015) for the systems evaluated in France. Therefore, the design value for the surface hydraulic loading rate may be the governing criterion, when compared with the design based on surface mass loading rates ( $\text{g m}^{-2} \text{ d}^{-1}$ ), since raw wastewater may be more diluted in Brazil, at least under dry weather conditions. For the same values of surface mass loading rates, higher surface hydraulic loading rates may be potentially adopted. Therefore, the importance of the hydraulics in the performance of the French system is another element that deserves further investigation for applications in warm regions, complementing the publications that have already focused on performance data.

This paper aims to investigate some of the hydraulic aspects mentioned here, considering the application in a warm climate country (Brazil), highlighting that very little research has been undertaken under these conditions. The system is the same as that investigated by Lana *et al.* (2013) and Manjate *et al.* (2015), with only the first stage of the French system, and with only two units in parallel in the first stage. In this paper, the performance of the system was assessed with two different pulse feeding times (3 min and 8 min) and instantaneous hydraulic loading rates ( $0.36 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$  and  $0.14 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$ ), in both cases using much less conservative values than the French specifications (Molle *et al.* 2005; Dotro *et al.* 2017).

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## MATERIAL AND METHODS

### System description

The VFCW is located at the Centre for Research and Training in Sanitation (CePTS) of the Federal University of Minas

Gerais (UFMG) and the Water and Sanitation Company of Minas Gerais (COPASA) in Belo Horizonte, Brazil (19°53'42" S, 43°52'42" W). The climate in the region, according to the Köppen classification system, is Cwa – tropical altitude, average annual temperature of 22.1 °C and precipitation of 1,540 mm year<sup>-1</sup>. The system used raw wastewater with the same characteristics as the city, after preliminary treatment (screens and grit removal).

The VFCW system was designed to treat wastewater generated by an equivalent population of 100 inhabitants following, with some constructive adaptations, the French recommendations from IRSTEA (previously CEMAGREF) (Boutin *et al.* 1997; Molle *et al.* 2005). The system is comprised by only the first stage and was originally built with the usual three units in parallel. Operation started in 2009, and in 2014 the system started operating with only two units in parallel, as part of the assessment of the applicability of these conditions in a warm climate. This study is related to these current operating conditions of only two filters. The dimensions of each filter and the characteristics of the filter medium are given in Table 1.

The system was planted with Tifton-85 (*Cynodon dactylon Pers.*), which is a hybrid specimen selected for its drought tolerance, for its potential exploitation as animal food (commonly used for horse and cattle feeding) and its capability of uniform distribution on the system surface (Cota 2011).

## Feeding system

Along with this research, two different types of emptying the accumulation box and feeding the filters were evaluated, leading to different pulse times and instantaneous surface hydraulic loading rates.

In Phase 1 (October 2013 to January 2016), box emptying and filters feeding were done by a positive displacement pump (Netzch, 3.7 kW or 4.96 HP). In Phase 2 (February 2016 to December 2017), the pump was substituted by a dosing bell siphon. It is seen that the study extended for a long period (28 months in Phase 1 and 23 months in Phase 2), allowing for representative results to be obtained in the system monitoring.

It should be mentioned that, in both phases, the grid of distribution pipes was also changed. In the first phase, it was comprised by a manifold and perforated laterals with orifices (as is usually done in the second stage of French systems; see Dotro *et al.* 2017; Paul *et al.* 2018). As this was prone to obstructions, given that it received raw wastewater, the grid was changed to a manifold with laterals with open ends and without orifices (as is typically done in the first stage of French filters; again see Dotro *et al.* 2017). However, this is not believed to have influenced the performance of the system, since it was merely associated with the problem of obstruction of the orifices in the long run. Analysing the study done by Paul *et al.* (2018), the number of feed points per unit area of the grid of distribution pipes

**Table 1** | Summary of filter characteristics

### Dimensions of each filter (m)

Length	Width	Depth	Surface area of each filter (m <sup>2</sup> )	Total surface area (m <sup>2</sup> )
9.4	3.1	0.7	29.1	2 × 29.1 = 58.2
Filter Media				
Layer	Depth (m)	Filter medium specifications	Grain-size curve analysis <sup>a</sup>	UC (d <sub>60</sub> /d <sub>10</sub> )
Top layer	0.40	Crushed stone (fine gravel) (specified as 2.4 mm–12.5 mm)	d <sub>10</sub> = 0.8 mm d <sub>30</sub> = 5.25 mm d <sub>60</sub> = 7 mm	8.75
Transition layer	0.15	Crushed stone (intermediate) (specified as 4.8 mm–25 mm)	d <sub>10</sub> = 7 mm d <sub>30</sub> = 13 mm d <sub>60</sub> = 19 mm	2.71
Drainage layer	0.15	Crushed stone (coarse gravel) (specified as 19–50 mm)	Not carried out	

Note: local material was used, and did not match exactly with French specifications.

d<sub>10</sub>, mesh diameter that allows 10% of the sample by mass to pass through (mm); d<sub>30</sub>, mesh diameter that allows 30% of the sample by mass to pass through (mm); d<sub>60</sub>, mesh diameter that allows 60% of the sample by mass to pass through (mm); UC: uniformity coefficient (d<sub>60</sub>/d<sub>10</sub>).

<sup>a</sup>Cota *et al.* (2011).

(5.7 orifices  $\text{m}^{-2}$  in our Phase 1) was nearly 47% of that used in their work (12.4 orifices  $\text{m}^{-2}$ ). Compared with Dotro *et al.* (2017), in both cases, the number of feed points per unit area was much higher than the maximum recommended of 1 point per 50  $\text{m}^2$ , or 0.02 points  $\text{m}^{-2}$  (in Phase 1, it was 5.7 orifices  $\text{m}^{-2}$ , and in Phase 2 it was 0.55 points  $\text{m}^{-2}$ ). Besides the fact that the density of feed points complied safely with the French recommendations, the liquid level during the pulses was maintained at 2 cm, that is, it also complied with the recommendations of 2 to 5 cm (Dotro *et al.* 2017). It can then be assumed that the areal distribution of liquid on the filter surface was satisfactory in both phases, what was also supported by visual analysis during the batches. Therefore, it is believed that, for the purposes of this study, the differences in the distribution grid between phases has not had important implications in terms of system performance.

### Loading and operating conditions

Each unit was fed for 7 days, while the other unit was resting for the same period. After 7 days of operation, the two cells were alternated, completing a total cycle of 14 days. The mean inflow in the unit in operation was  $13 \text{ m}^3 \text{ d}^{-1}$ , divided into 24 batches of  $0.53 \text{ m}^3$  every hour, resulting in a surface hydraulic loading rate (HLR<sub>s</sub>) in the unit in operation of  $0.45 \text{ m}^3 \text{ m}^2 \text{ d}^{-1}$ , close to the French specification of  $0.37 \text{ m}^3 \text{ m}^2 \text{ d}^{-1}$  (Molle *et al.* 2005; Morvannou *et al.* 2015). This operational condition was kept for the entire study period. Although the HLR<sub>s</sub> did not change throughout the study, the modification of the feeding system induced a change in the wastewater distribution, and subsequently an increase in feeding time and a decrease in the instantaneous hydraulic loading rate. In Phase 1, with the pump, the feeding time was shorter (3 min) and the instantaneous hydraulic loading rate was higher ( $0.36 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$  or  $6.0 \text{ L m}^{-2} \text{ min}^{-1}$ ). In Phase 2, with the siphon, which had a smaller capacity compared with the pump, the feeding time was longer (8 min) and the instantaneous hydraulic loading rate was inversely lower ( $0.14 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$  or  $2.3 \text{ L m}^{-2} \text{ min}^{-1}$ ). It should be noted that, in both cases, the instantaneous HLR was much lower than the minimum recommended by the French specifications, which are  $0.5 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$  ( $8 \text{ L m}^{-2} \text{ min}^{-1}$ ), according to Dotro *et al.* (2017), or  $0.6 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$  ( $10 \text{ L m}^{-2} \text{ min}^{-1}$ ), according to Molle *et al.* (2005), and also to German recommendations for vertical wetlands receiving primary effluent –  $6 \text{ L m}^{-2} \text{ min}^{-1}$  (DWA 2015) (Paul *et al.* 2018). These aspects are important elements

in this study and the main driver for the comparison of both phases and feeding conditions. Table 2 presents a summary of the feeding systems and loading conditions applied in both phases of the study.

### Sampling, monitoring and data collection

In order to evaluate the treatment performance associated with the two different feeding types, physical-chemical analyses were performed on a set of samples collected in the raw wastewater and treated effluent. Sampling frequency (influent and effluent) was once a week for most of the study period, with collection on the third day of the feeding period of 7 days, following the methodology adopted in previous research in the same system (Cota 2011; Moraes 2012; Lana *et al.* 2013; Manjate *et al.* 2015). The influent was characterized by grab samples during the whole time of filling the tank (1 h), collected before entering the storage tank (square tank: volume  $1 \text{ m}^3$ ) to avoid influence of sedimentation that would take place inside the tank. In the case of the effluent samples, they were taken in the outlet chambers covering the duration of the interval between batches (1 h). Since the effluent flows and concentrations vary substantially during each batch, a differentiated sampling strategy was adopted in order to seek to approximate to a representative flow-proportional composite sample from the effluent. During the first minutes, in which the outflow was higher, sampling frequency was also higher, and at the end of the batch period, when the outflow was lower, so was the monitoring frequency: 1 L samples were collected from the outlet pipe with an interval of 5 min for the first four samples and 10 min for the last three samples. The seven sub-samples were then poured and mixed in the same plastic bucket to obtain a single composite sample. The following parameters were analysed in the influent and effluent: COD, BOD<sub>5</sub>, TSS and TKN. The parameters were determined following the *Standard Methods for the Examination of Water and Wastewater* (APHA/AWWA/WEF 2012). Dissolved oxygen (DO) and redox potential (ORP) were measured *in situ* using HACH DO023.53.90050/HQ40D probes. The measurement of effluent flow rates resulting from each pulse was undertaken by volumetric measurement of the effluent volume (using graduated buckets) and time measurement (using chronometers).

For the comparative statistical analysis between the effluent concentrations and removal efficiencies achieved in the two phases, the Mann-Whitney U-test (considering a

**Table 2** | Feeding systems characteristics and loading operations conditions

Parameter	Feeding systems characteristics	
	Phase 1	Phase 2
Grid of distribution pipes	As is usually done in the second stage of French systems	As is typically done in the first stage of French filters
Number of feeding points	166 orifices in perforated pipes	16 points at the end of each lateral pipe
Diameter of feeding point	10 mm orifice diameter (25 mm pipe diameter)	20 mm end of pipe diameter
Feeding point density	5.7 orifices·m <sup>-2</sup>	0.55 points·m <sup>-2</sup>
Density of drainage pipe at the bottom	2 drainage pipes, 9.2 m each, total length 18.4 m; 29.1 m <sup>2</sup> system area (0.63 m <sup>-2</sup> ); 100 mm diameter pipe; orifice diameters of 12 mm at every 10 cm of drainage pipe length	
Pulse feeding system	Positive displacement pump	Dosing bell siphon
Operating loading conditions		
Phase	Phase 1	Phase 2
Feed time during each batch (min)	3	8
Feeding flow (m <sup>3</sup> per batch)	0.53	0.53
Applied HLR (m <sup>3</sup> m <sup>-2</sup> d <sup>-1</sup> )	0.45	0.45
Water level on top of the filter during the pulse (cm)	0.53 m <sup>3</sup> batch <sup>-1</sup> /29.1 m <sup>2</sup> = 0.02 m = 2 cm	
Instantaneous HLR during pulse (L m <sup>-2</sup> min <sup>-1</sup> )	6.0	2.3
Number of batches per day	24	24
Interval between batches (min)	60	60
Alternation frequency (feeding/resting period) (d)	7 days feeding/7 days resting	7 days feeding/7 days resting

HLR, hydraulic loading rate.

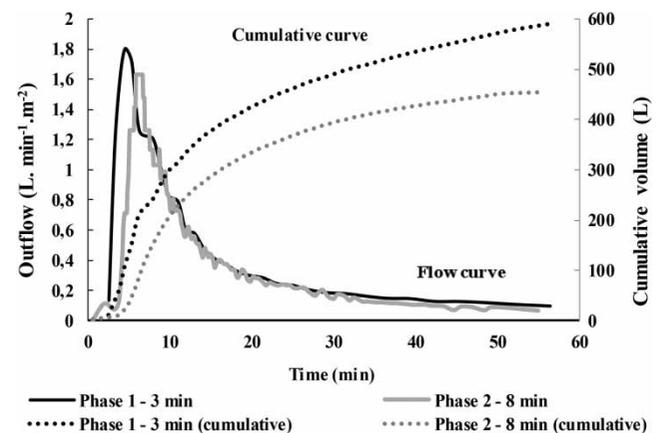
Phase 1: October 2013–January 2016. Phase 2: February 2016–December 2017.

5% significance level) was applied, using the software STATISTICA, version 10.0 Enterprise.

## RESULTS AND DISCUSSION

### Outflow hydraulic profiles

Figure 1 presents the variation of the effluent flow over time and the cumulative volume during the feeding pulse measured in the third day of the cycle (feeding cycle of 7 days). Each measurement represents the typical profile during both phases, and they were undertaken with a one-year interval (April 2015–April 2016). The shapes of both curves were substantially similar. The curves of the outflow increased sharply up to the peak and then were followed by a slow reduction, represented by the tails in the curves. In Phase 1 (feeding time of 3 min) the peak occurred after 5 min, reaching the value of 1.10 L s<sup>-1</sup> (0.038 L s<sup>-1</sup> m<sup>-2</sup> or 2.28 L min<sup>-1</sup> m<sup>-2</sup>). In Phase 2 (longer feed time of 8 min),



**Figure 1** | Variation of the effluent flow over time and outlet cumulative volume during first feeding pulse in the third day of operation in both phases of the investigation.

the curve showed the same behaviour as in Phase 1, but, as expected, the peak was lagged, taking place after 8 min feeding, reaching the peak with a value of 0.85 L s<sup>-1</sup> (0.029 L s<sup>-1</sup> m<sup>-2</sup> or 1.74 L min<sup>-1</sup> m<sup>-2</sup>).

The behaviour of the curve, characterized by the sharp and fast increase and immediate decrease of the effluent flow, demonstrates a good hydraulic performance of the units and suggests that an effective oxygen transfer can occur through convection and diffusion (Kayser & Kunst 2005). According to Molle *et al.* (2006), after the pulse loading, the infiltration rate decreases during the operation as a result of moisture saturation in the filters. Therefore, preferential pathways of water into the bed can explain the differences observed in the curves of effluent outflow over time. Other factors, such as type of filter material, grain size distribution, particle and bulk density, porosity, hydraulic conductivity, water saturation level in the pores and water distribution in the upper part of the surface, interfere in the dynamics and hydraulic functioning of the system (see Langergraber *et al.* 2009; Paul *et al.* 2018).

Cumulative volume over time was also calculated and is plotted in Figure 1. The analysis showed that in Phase 1, 50% of the volume applied (total volume 0.53 m<sup>3</sup>) was recovered after 9 min and 100% was obtained after 23 min. In Phase 2, 50% of the volume applied was recovered after 11 min (as expected, slightly higher than in Phase 1). However, 100% of the fed volume could not be

obtained (recovery of only 89%) because, after 60 min, a new batch started. The different feeding and infiltration rates in both phases, together with the increment of the deposit layer on the filter surface after one year, can explain the differences of cumulative profiles over time.

## Removal performances

Values of the applied surface hydraulic loading rate (HLR<sub>s</sub>) and surface organic loading rate (OLR<sub>s</sub>), together with influent and effluent concentration values, average removal efficiencies and *p*-values on the Mann-Whitney U-test comparing the effluent concentrations and removal efficiencies in both phases are summarized in Table 3. Throughout the study, the resulting applied organic loading rates were close to 300 g COD m<sup>-2</sup> d<sup>-1</sup> for the filter in operation, as recommended for the French design (Molle *et al.* 2005). In terms of statistical analysis, comparing phases 1 and 2, the applied organic loading rates were not significantly different (*p* = 0.7570), which is an important element in excluding organic loadings as a possible difference in the behaviour of both phases.

**Table 3** | Descriptive statistics for each operational phase and *p*-values of the Mann-Whitney U-test comparing both phases (effluent concentrations and removal efficiencies)

Parameter	System 2 units – 24 daily feed pulses of 0.53 m <sup>3</sup>				<i>p</i> -values Phase 1 × Phase 2 (Mann-Whitney U-test)
	Phase 1 <sup>a</sup>		Phase 2 <sup>a</sup>		
Feed time (min)	3		8		–
Applied HLR (m <sup>3</sup> ·m <sup>-2</sup> ·d <sup>-1</sup> ) <sup>b</sup>	0.45		0.45		–
Applied organic loading rate (g COD·m <sup>-2</sup> ·d <sup>-1</sup> ) <sup>b</sup>	222 (29) <sup>c</sup>		213 (102)		0.7570
Concentration values	Influent	Effluent	Influent	Effluent	–
COD (mg·L <sup>-1</sup> )	441 (123)	87 (48)	477 (229)	151 (61)	0.0001*
BOD <sub>5</sub> (mg·L <sup>-1</sup> )	237 (70)	49 (26)	319 (99)	62 (29)	0.1036
TSS (mg·L <sup>-1</sup> )	190 (82)	34 (23)	402 (312)	71 (56)	0.0008*
TKN (mg·L <sup>-1</sup> )	36 (9)	10 (5)	46 (14)	20 (9)	0.0007*
DO (mg·L <sup>-1</sup> )	0.4 (0.3)	4.5 (1)	0.5 (0.4)	4.1 (0.9)	0.0411*
ORP (mV)	–32 (33)	251 (42)	–3 (80)	243 (78)	0.9076
Removal efficiencies %					
COD	79 (13)		63 (17)		0.0005*
BOD <sub>5</sub>	78 (12)		81 (8)		0.9931
TSS	81 (14)		75 (22)		0.6033
TKN	71 (15)		54 (17)		0.0154*

<sup>a</sup>Phase 1: feeding by pump; October 2013–January 2016. Phase 2: feeding by dosing bell siphon; February 2016–December 2017.

<sup>b</sup>Hydraulic and organic loading rates are based on the unit in operation.

<sup>c</sup>Mean values are presented (values between brackets are standard deviations).

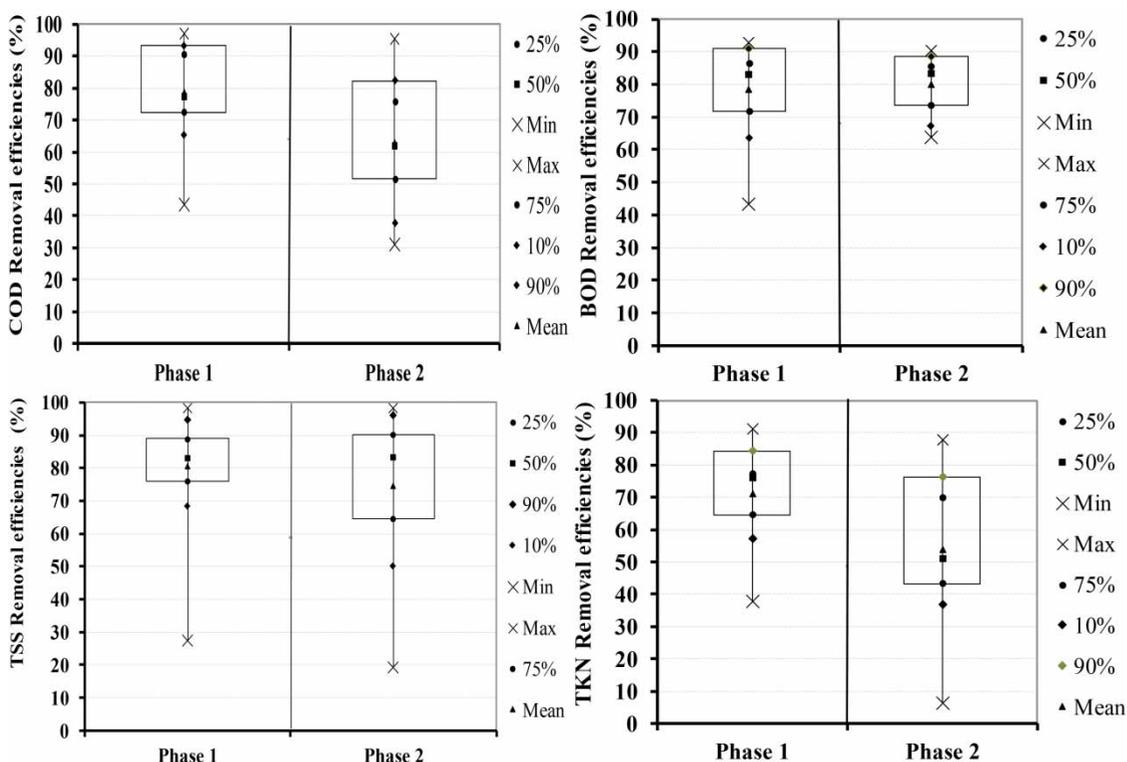
\**p*-values ≤ 0.05: means samples are significantly different.

Removal efficiencies for each specific pollutant and phases will be discussed in the subsequent sections. For the overall period (phases 1 and 2 together, 51 months of operation), mean removal efficiencies of 69% for COD, 79% for BOD, 78% for TSS and 58% for TKN were obtained, which can be considered satisfactory for developing countries, especially if stringent discharge standards are not in place. The values are also similar to those reported in a broad survey undertaken by *Morvannou et al. (2015)* for the classical first stage of the French system (77%, 83% and 59% for COD, TSS and TKN removal, respectively). When interpreting the efficiencies obtained, it should be always remembered that, in the present study, only two units were used in the first stage, representing two-thirds of the usual area of a typical first stage of the French system. *Moraes (2012)* previously worked in the same system as the one in this study, with two units in parallel and the same HLR, with feeding by pump during 5 min and similar instantaneous hydraulic loading rate ( $0.38 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$  or  $6.5 \text{ L m}^{-2} \text{ min}^{-1}$ ), reported removal efficiency values of 71% for COD, 79% for BOD, 78% for TSS and 50% for TKN.

## COD and BOD

Satisfactory removal efficiencies were observed for COD and BOD<sub>5</sub> throughout the study. Mean COD removal value in Phase 1 (79%) was significantly higher than in Phase 2 (63%), based on the Mann-Whitney U-test ( $p \leq 0.05$ ). In the case of BOD<sub>5</sub>, the values of removal efficiencies behaved in a contrary way, that is, the system with feeding time of 3 min (Phase 1) had 78% removal, whereas with feeding time of 8 min (Phase 2), the removal efficiency was 81%, although there was no significant difference between both phases ( $p = 0.9931$ ). But it should be noted that in Phase 2, the mean influent BOD concentration, and thus the applied organic loading rate, was substantially higher, which was not the case with COD.

The results presented in *Table 3* show differences between the influent and effluent concentrations obtained between the two phases. Mean effluent values in Phases 1 and 2 were 87 and 151  $\text{mg L}^{-1}$  for COD, and 49 and 62  $\text{mg L}^{-1}$  for BOD<sub>5</sub>, respectively (see *Figure 3*). It can be considered that the system presented a satisfactory performance in terms of organic matter removal, similar to the



**Figure 2** | COD, BOD, TSS and TKN removal efficiencies in both phases along the whole research period.

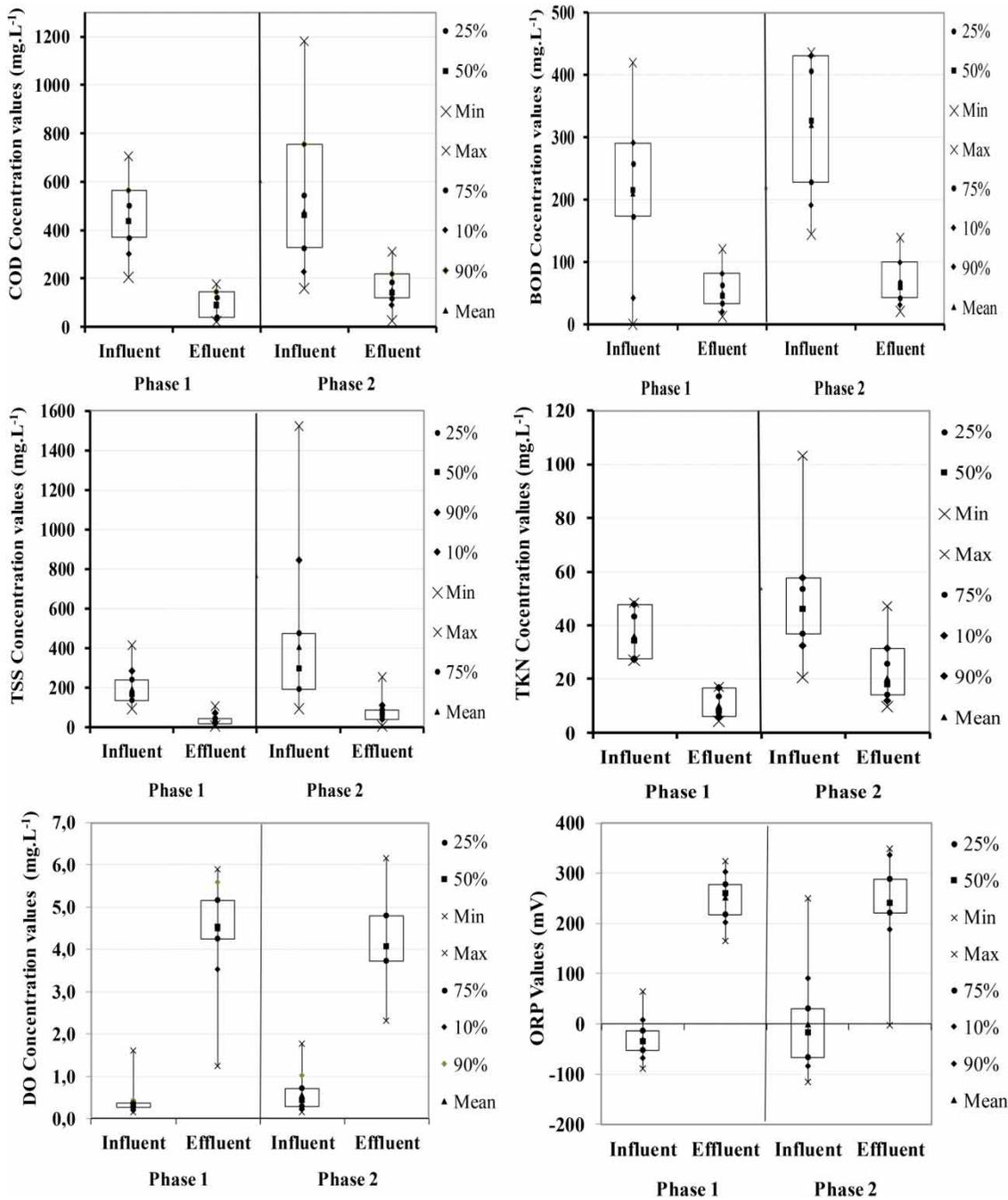


Figure 3 | Influent and effluent, COD, BOD, TSS, TKN, DO concentrations and ORP values from each phase along the whole research period.

broad survey carried out by *Morvannou et al. (2015)*, who reported a mean COD value of 126 mg L<sup>-1</sup> for the first stage of the French system. A comparison of effluent concentrations, based on Mann-Whitney U-test, showed that there were significant differences between both phases in relation to COD ( $p \leq 0.05$ ), but not for BOD<sub>5</sub>. Again, this may be due to the different organic matter characteristics

of the influent wastewater, as represented by BOD and COD, as discussed in the paragraph above.

### Total suspended solids

Mean removal efficiencies of TSS were 81% and 75% for Phase 1 and Phase 2, respectively (Table 3 and Figure 2).

These values are considered satisfactory for developing countries and similar to those reported in the broad survey undertaken by *Morvannou et al. (2015)* (83%). There were no significant differences between phases ( $p = 0.6033$ ). In relation to mean effluent concentrations of TSS ( $34 \text{ mg L}^{-1}$  and  $71 \text{ mg L}^{-1}$  for the first and second phases, respectively), the statistical analysis showed that there were significant differences between the two phases studied ( $p = 0.0008$ ). The lower removal in Phase 2 could be explained by the fact that, over two months (March–April 2017), in the second cell the deposit layer was inadvertently removed during cutting of the plants. The removal of the deposit layer contributed to the increase of the percolation velocity and a decrease of the solids removal capacity at the surface layer.

## Nitrogen

Due to the oxygen transfer in the system associated with the batch feeding of the influent and the maintenance of aerobic conditions, nitrification is likely to take place in VFCWs. In the first stage, partial, and not full, nitrification is expected, due to the competition for oxygen between heterotrophs and autotrophs, as supported by the results obtained in the surveys done by *Molle et al. (2005)* and *Morvannou et al. (2015)*. According to studies undertaken by *Prost-Boucle & Molle (2012)* in the French system, nitrification occurred mainly in the aerobic upper part of the filter. In agreement with *Kantawanichkul et al. (2009)*, the low potential for complete nitrification in vertical wetlands is associated with the operation and physical structure of the systems, which do not provide sufficient holding time to allow contact with the bacteria that are responsible for the nitrification.

The system was able to perform a partial removal of the TKN present in the influent, indicating the presence of an oxidative (aerobic) environment. It was observed that, although reaching a satisfactory percentage of mean removal efficiency, especially taking into account that only two units were used in the first stage, in Phase 2 the mean removal efficiencies (54%), were significantly lower than in Phase 1 (71%) (*Table 3*). Lower removals in Phase 2 may be linked to a possible poorer application of wastewater on the filter surface, associated to an increase in the feeding time (from 3 to 8 min) that brought a decrease in the instantaneous hydraulic loading rate (from  $6.0$  to  $2.3 \text{ L m}^{-2} \text{ min}^{-1}$ ). These hydraulic conditions could increase the ammonia saturation locally and affect the effluent concentration. According to *Molle et al. (2006)*, good draining

conditions favour low water contents in the filter, better oxygenation and higher nitrification due to  $\text{NH}_4^+$  adsorption and nitrification during the rest period.

Unfavourable conditions could be minimized by increasing the pulse volume and the rest period between pulses, that is, decreasing the number of daily batches. Fewer batches per day, with higher volumes per batch, may induce a higher suction of air following the liquid percolation which may assist in enhancing aerobic conditions within the bed, and thus, possibly improving nitrification (*Molle et al. 2006*). However, it should be remembered that, under warm climate conditions, the option of having more batches per day, with shorter intervals between batches, can be justified by the fact that there is a shorter storage time of the raw wastewater in the feed box, decreasing the risks of the release of malodours, which are a major concern at higher temperatures. The possible influence of DO and redox potential on nitrification is discussed in the subsequent section.

## DO and redox potential

Similar to other studies developed in the first stage of VFCW-FS, concentrations of DO increased from influent to effluent (*Figure 3*). During the whole period of operation with both types of feeding systems, the oxygen concentrations at the outlet were positive, with Phase 1 having significantly higher concentrations (mean  $4.5 \text{ mgO}_2 \text{ L}^{-1}$ ) compared with Phase 2 (mean  $4.1 \text{ mgO}_2 \text{ L}^{-1}$ ). Redox potential also increased substantially from influent to effluent, reaching high values (*Figure 3*), which are expected to sustain nitrification.

*Lana et al. (2013)*, in a former study carried out in the same treatment plant, obtained mean concentrations of  $5.1 \text{ mgO}_2 \text{ L}^{-1}$  in the effluent. Although they were higher, the values were determined for a different operational regime from that established in this research: the system had only 2 years of operation, and worked with the same hourly batch frequency, but with 2.5 days of feeding followed by 4.5 days of rest and with 3 units in the first stage.

In the comparison with the results obtained by *Lana et al. (2013)*, it is important to analyse that now, after more years of operation, the oxygen transfer conditions to the filter bed may have been affected, mainly influenced by the greater accumulation of solids in the upper part of the filter (average of 6.6 cm solids layer above filter bed), the feeding of each unit lasting a longer period of time (7 days, as opposed to 2.5 days before) and the change in the raw wastewater distribution system. In Phase 2, the feeding

time was almost tripled, increasing from 3 to 8 min, due to the lower flow capacity of the siphon, as compared with the pump. It is well known that an increase in the contact time, caused by the increase in feeding time, may have an influence on the decrease of the mean concentration values of DO, as found in Phase 2 ( $4.1 \text{ mgO}_2 \text{ L}^{-1}$ ). Molle (2014) emphasizes that hydraulic and organic loads must be well controlled in order to favour the mineralization of this layer. Otherwise, there are limitations of oxygen transfer processes (convection and diffusion) due to excess surface water, influencing the system performance.

The results suggest that the established conditions favoured the aerobic processes for the degradation of organic matter and nitrification. Torrens *et al.* (2009), although investigating a slightly different configuration (vertical flow systems – second stage – fed with pond effluents and using sand as filtering material), emphasize that the lack of compliance with recommendations for feeding and resting periods (3–4 days of feeding/7 days of rest) for the climatic conditions of France increases the accumulation of the organic layer on the surface, causing problems of clogging, a fact not observed when the recommended operating criteria are respected. Kania *et al.* (2018), investigating in several full-scale French constructed wetlands, emphasize that the increase of the surface layer's thickness may also reduce the permeability of the filter and lead to clogging, thereby reducing treatment performance. However, it should be always remembered that the current research was undertaken at a warm climate, that may lead to different behaviours compared to those observed in France.

## CONCLUSIONS

The results indicated differences and similarities in the behaviour of both phases, as associated with the pulse time and resulting instantaneous surface hydraulic loading rates. In both phases of the study – Phase 1 (feeding time of 3 min and instantaneous HLR of  $0.36 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$  or  $6.0 \text{ L m}^{-2} \text{ min}^{-1}$ ) and Phase 2 (feeding time of 8 min and instantaneous HLR of  $0.14 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$  or  $2.3 \text{ L m}^{-2} \text{ min}^{-1}$ ) – the hydraulic behaviour was capable of leading to an effective transfer of oxygen to the treatment units. Mean values of 4.5 and  $4.1 \text{ mg L}^{-1}$  for DO and 251 and 243 for ORP were obtained in Phases 1 and 2, respectively.

A shorter duration of pulse time with higher instantaneous HLR (Phase 1) favoured good drainage and a low water content in the filter, obtaining a greater cumulative

volume. The different feeding and infiltration rates in both phases, together with the increment of the deposit layer on the filter surface after one year, can explain the differences of cumulative profiles over time.

In the first stage of the vertical wetland (French system) using only two filters, with 24 batches per day for 7 days of operation, followed by 7 days of rest, good global removal efficiencies were obtained throughout the monitoring period, with mean removals of 69%, 79%, 78% and 58% for COD, BOD<sub>5</sub>, TSS and TKN, respectively.

Regarding the different strategies evaluated, the importance of pulse time was observed. Effluent concentrations of some constituents were significantly affected in a negative way, with higher concentration values having been obtained with the increased feeding time and decreased instantaneous HLR. Lower feeding time (Phase 1, 3 min) generally favoured an increase in the removal of contaminants, but even with the longer feeding time (Phase 2, 8 min), the concentrations in the effluent and the removal of the pollutants can be considered good.

The study is not conclusive about the implications resulting from the fact that the applied instantaneous HLR was lower than the literature recommendations, because this was the case in both phases. However, the overall results suggest that the performance was satisfactory and oxygenation took place throughout the period.

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