Research Paper

Hybrid constructed wetlands system with intermittent feeding applied for urban wastewater treatment in South Brazil

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ABSTRACT

Hybrid constructed wetlands composed by vertical flow constructed wetland (VFCW) followed by horizontal subsurface flow constructed wetland (HFCW) are a wastewater treatment technology employed worldwide. However, there are few studies of their application in Brazil. Treatment performance is not achieved directly after the start of operation and may change according to external conditions over time. This paper evaluated a VFCW–HFCW hybrid system applied to treat urban wastewater in southern Brazil during the first 70 operational weeks. The system was operated with cycles of rest and feed periods. The results point to the first 10 weeks of operation as a transitioning period, especially for VFCW, after which chemical oxygen demand (COD) (from 77% to 90%) and total suspended solids (TSS) (from 90% to 100%) removal performances stabilized and reached their peak rates. Factors such as rainfall precipitation, macrophytes' adaptation, and time of operation affected pollutants' removal. Regardless of the fluctuations throughout the period, the hybrid system presented resilience by generating excellent average removal rates. It showed a mean removal efficiency of 99% for TSS, 98% for COD, 69% for total nitrogen (TN), 91% for NH_4^+-N, and 96% for P-PO_4^{3-}. Moreover, the effluent was always suitable to be discharged into the environment according to Brazilian national and state regulations.

Key words | hydraulic regime, startup, temporal performance, *Thypha domingensis*, vertical and horizontal flow constructed wetlands

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INTRODUCTION

Constructed wetlands (CW) are a wastewater treatment technology employed worldwide. Their main advantages over conventional wastewater treatment plants reside in their simple operation and low maintenance, energy requirements, and initial capital cost, which altogether culminates in positive environmental and social outcomes (Ávila & García 2015). Over the years, many advances and modifications have been proposed to improve the treatment performance of CW. Thus, nowadays, these systems are employed under a large variety of design and operation conditions. One of those variations is the arrangement of different CW in series, known as CW hybrid systems.

Among the CW hybrid systems, vertical flow (VFCW) followed by horizontal subsurface flow (HFCW) is the main arrangement employed in the world today (Vymazal 2013), and its study started more than half a century ago (Seidel 1965). Despite that, there are a very limited number of CW hybrid systems in Brazil and even less reliable

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monitoring data for all real, pilot, and bench scale systems (Machado *et al.* 2017). The dissemination of such technology in Brazil would benefit the poor Brazilian sanitation coverage, especially for low-density regions with sensitive environments, in which advanced levels of wastewater treatment are required but large investments are not feasible.

VFCW–HFCW hybrid systems can reach a high wastewater treatment level since they present various pollutants' removal and transformation pathways. The diverse microbiological structure present in the bed media of both units provides various ways to remove carbonaceous organic matter and nitrogen compounds. In general, VFCW is intended to create an aerobic environment, aiming to remove organic matter and promote ammonia nitrogen oxidation. On the other hand, HFCW creates a predominantly anoxic and anaerobic environment, where organic matter is further removed and the reduction of oxidized nitrogenous compounds is favored.

One operational strategy that has already been used is intermittent wastewater application in VFCW. The intermittence promotes air drag into the bed media, enhancing nitrification and organic matter oxidation, which, thus, improves overall treatment performance. In this modality of wetlands, the main source of oxygen to the interior of the filter media occurs by the convection and diffusion of the atmospheric air (Platzer 1999; Kayser & Kunst 2005). For VFCW operated with sand as bed medium, the amount of oxygen diffused in the medium is $1\ \mathrm{g\ O_2\ m^{-2}\ h^{-1}}$. In relation to the convection mechanism, the oxygen input is dependent on hydraulic loading rate and the retention time (Platzer 1999). Furthermore, the use of a hydraulic regime based on alternation of phases of feed and rest allows for controlling the growth of the attached biomass, to maintain aerobic conditions within the filter bed and to mineralize the organic deposits accumulated on the bed surface, increasing CW treatment performance (Molle *et al.* 2008). In this way, the existence of operation and resting periods (i.e., 3.5 days of feeding and rest periods in the week), through the establishment of alternate operation, extends the system's lifespan. However, in Brazil, the few monitored CW hybrid systems usually operate with continuous feeding (i.e., they are operated every day of the week) (Sezerino *et al.* 2012; Machado *et al.* 2017).

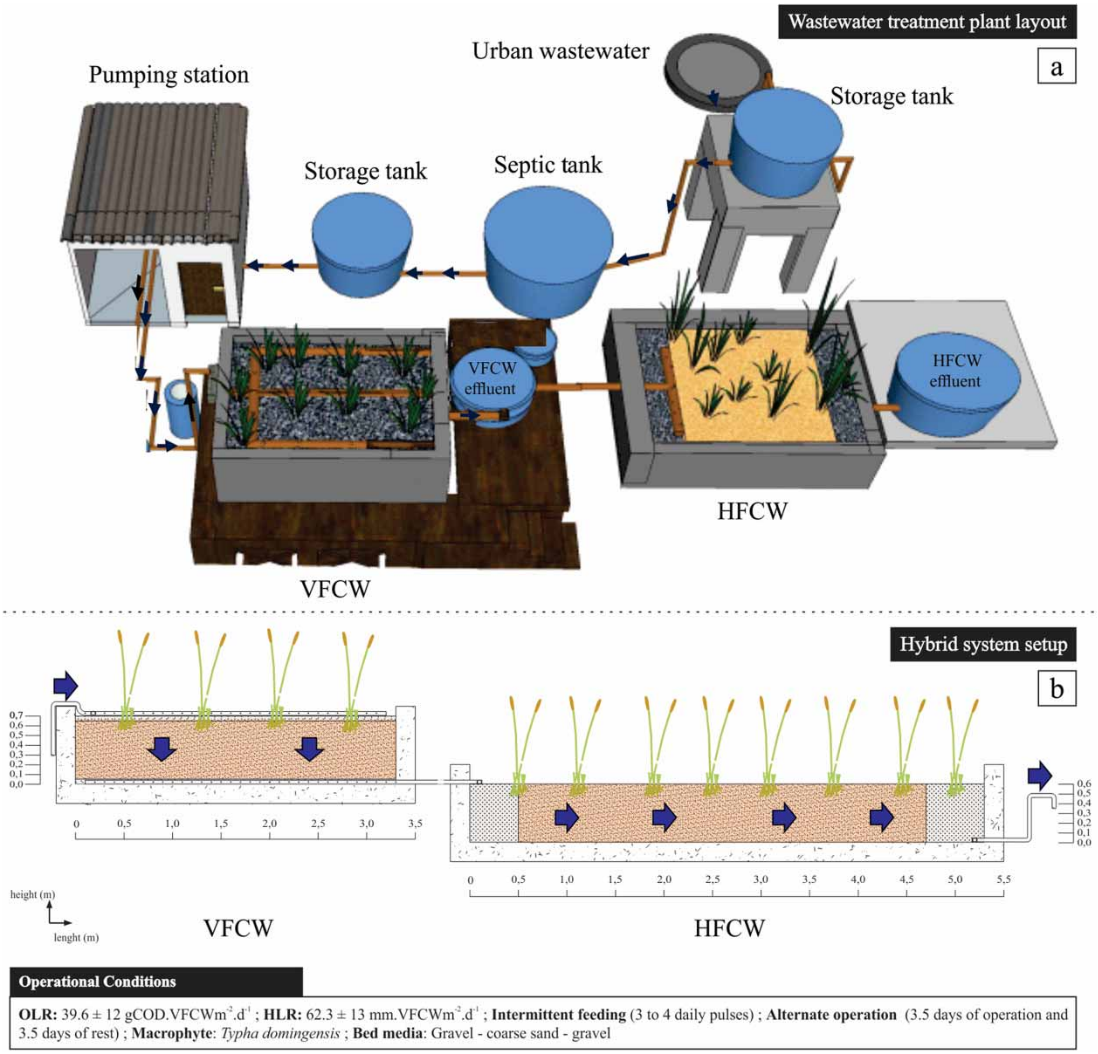
In order to disseminate this technology to the Brazilian context, local investigation studies with reliable monitoring data are required since the treatment performance (and consequently system design) are highly dependent on the climate (i.e., air temperature, radiation hours, rainfall, among others) and operation strategies. Furthermore, the technology implementation will depend not only on the treatment performance, but also on the availability of land, local macrophytes, and material for bed media (i.e., the feasibility of its implementation). Brazil has generally warm temperatures, extensive radiation hours, large biodiversity, and available land, which all favor the implementation of CW systems.

Faced with the lack of data on hybrid CW systems in Brazil and the country's favorable conditions for its implementation, the aim of this study was to evaluate the behavior of a pilot-scale hybrid system (VFCW–HFCW) with hydraulic regime based on feed and rest periods. To the best of the authors' knowledge, this is the first study to monitor a VFCW–HFCW hybrid system in Brazil operated with feed and rest periods. Moreover, this study provides a general discussion on its treatment performance, including load removal, associated with weather and plant monitoring, from the system's startup to more than one year of operation. This can be particularly helpful for practitioners who wish to implement this technology in the Brazilian context.

METHODS

The experimental treatment plant

The treatment plant was implemented in July of 2015 and is located in southern Brazil (27°35′48″ latitude; 48°32′57″ longitude) in a subtropical climate (average air temperature of 20 °C and monthly average precipitation of 113 mm). The treatment plant comprises a primary treatment conducted by septic tank ($1.5\ \mathrm{m^3}$) followed by a VFCW and HFCW operated in series. First, the urban wastewater is collected by a lift station set in a nearby manhole of the municipal sewerage system and pumped into the septic tank. Subsequently, the wastewater is conveyed by intermittent pumping to the VFCW and by gravity to the HFCW. The hybrid system was designed to treat the equivalent daily volume of the contribution from a single Brazilian house (5 PE) and had a superficial area equal to $7.5\ \mathrm{m^2}$ (3.3 length × 2.3 width × 0.7



Operational Conditions

OLR: 39.6 ± 12 gCOD.VFCWm^{-2}.d^{-1} ; **HLR:** 62.3 ± 13 mm.VFCWm^{-2}.d^{-1} ; **Intermittent feeding** (3 to 4 daily pulses) ; **Alternate operation** (3.5 days of operation and 3.5 days of rest) ; **Macrophyte**: *Typha domingensis* ; **Bed media**: Gravel - coarse sand - gravel

Figure 1 | Evaluated hybrid system: (a) scheme of the wastewater treatment plant layout, without scale; (b) scheme of the hybrid system setup and a summary of the operational conditions.

height) and 16 m^2 (5.3 length × 3.0 width × 0.60 height) for the VFCW and HFCW, respectively (Figure 1).

Both VFCW and HFCW had coarse sand as bed media ($d_{10} = 0.21$ mm and uniformity coefficient (Cu) = 5.10 for VFCW; $d_{10} = 0.29$ mm, and Cu = 4.05 for HFCW) with layers of gravel at the inlet and outlet. Following the water flow, the VFCW had a total height of 0.70 m (0.05 m of gravel, 0.60 of coarse sand, 0.05 m of gravel), while the HFCW had a total length of 5.30 m (0.50 m of gravel, 4.20 m of coarse sand, 0.60 m of gravel). The HFCW had a total height of 0.60 m and the saturation level was set at 0.50 m. The macrophyte *Typha domingensis* was planted with a density of 4.20 and 3.30 cuttings.m^{-2} for the VFCW and HFCW, respectively. Pruning of the macrophytes was performed every three months for VFCW and HFCW. After 24 weeks of operation, an unharvesting strategy was assessed.

Considering the surface area of VFCW, the hybrid system was operated under an average organic loading rate (OLR) of 40 ± 12 g COD.m^{-2}.d^{-1} and a hydraulic loading rate (HLR) of 63 ± 13 mm.d^{-1}. The VFCW operation was set with intermittent feeding (3 to 4 pulses per day at 8:00 a.m., 11:00 a.m., 2:00 p.m., and 5:00 p.m.) and with cycles of 3.5 days of operation followed by 3.5 days of rest. Each pulse lasted around 2 minutes, with an input of 150 L. The HFCW had a theoretical residence time equal to 6.15 operational days or 9 consecutive days, considering the rest period.

Flow rates were continuously measured throughout the monitoring period. Inflow rate measurements were made during each sampling for water quality monitoring. The inflow was measured by using a container of known volume (approximately 40 L). The time needed to fill it was measured and then the flow rate was calculated. Outflows from the VFCW and HFCW were measured continuously. A tilting device with known volume (approximately 3 L) was set up at the outlet of both VFCW and HFCW. Each time the device was filled up, it tilted and emptied itself, returning immediately to its primary position. At this moment, the time and rank of the tilting was recorded in a data logger, allowing the measurement of total treated volume and the discharge rate for each CW. In this way, the results are expressed on a mass balance basis considering the evapotranspiration as the difference between the sum of the applied hydraulic loading and the rainfall and the output discharge. The mass balance was done for every week in order to guarantee that there was no remaining discharge after the rest periods. Moreover, the treatment performance of the hybrid CW system is presented both as average concentration removal efficiency as well as applied and removed pollutant loading rates.

Water quality monitoring

The water quality monitoring lasted 70 weeks (from June 2015 to September 2016) since the first day of plant operation. Sampling was done at the inlet and outlet of each unit of the hybrid system. Until the 24th week, sampling and physical-chemical analyses were done weekly. After that, the frequency changed to twice a month.

The evaluated parameters were: pH, alkalinity, total suspended solids (TSS), chemical oxygen demand (COD), total nitrogen (TN), ammonium nitrogen (NH_4^+-N), nitrite nitrogen (NO_2^-N), nitrate nitrogen (NO_3^-N), and orthophosphate phosphorus (PO_4^{3-}P). The analysis of all parameters followed APHA (2005) methodologies, except the parameter NH_4^+-N, which followed Vogel's (1981) recommendations. All parameters with the exception of COD had the samples filtered prior to analysis and refer to the soluble fraction.

Statistical data analyses

Normality of the data of water quality parameters was tested by the Shapiro–Wilk test. Furthermore, the Pearson linear correlation test was performed in order to study the monotonicity and the strength of the correlations between air temperature and the physical and biological parameters evaluated in the influent and effluent of each CW unit. Efficiency was calculated in regard to influent and effluent of each unit or the whole system. All statistical analyses were performed by means of Statistic 7.0 software (StatSoft Inc. 2004).

RESULTS AND DISCUSSION

In general, based on 70 weeks of monitoring and operation, the hybrid system showed an excellent (>90%) removal of organic matter, total suspended solids, orthophosphate phosphorus, and ammonium nitrogen (Table 1). Moreover, the mean evapotranspiration rate was of 6 ± 0.6 $mm.d^{-1}$ in the VFCW and 1 ± 1 $mm.d^{-1}$ for HFCW. We stress that for both VFCW and HFCW, a low evapotranspiration was identified over the monitoring period (4.7 to 6.2 $mm.d^{-1}$ for VFCW and 0.6 to 3.2 $mm.d^{-1}$ for HFCW).

Carbonaceous organic matter performance

The average COD removal on the hybrid system was 98 ± 1%. Nevertheless, the hybrid system showed a variation in treatment performance throughout the monitoring. The main identified temporal behavior was the moment of startup of the hybrid system (Figure 2). Until the 10th week of operation, the COD mean removal efficiency of the VFCW was limited to 77 ± 7%, with minimum and maximum rates of 63% and 87%, respectively. Afterwards, the removal increased to 90 ± 5%, within a range of 75% to 99%. It is inferred, therefore, that the period of 10 weeks was the time that the microorganism and plant communities needed to reach their stabilization and offer their optimal removal efficiencies in the VFCW. On the other hand, even though the HFCW showed a variation in its effluent COD within the same interval of time, the HFCW did not greatly vary its efficiency during this period (81 ± 16% to 85 ± 15%, before and after the 10th week, respectively).

Table 1 | Mean concentrations and standard deviation of the evaluated physical-chemical parameters, mean organic and inorganic applied and removed loading rates, mean applied hydraulic rate and mean removal efficiencies of influent and effluent for the VFCW, HFCW, and hybrid system

Parameters *n* = 27	**VFCW influent**	**VFCW removal (%)**	**VFCW effluent and HFCW influent**	**HFCW removal (%)**	**HFCW and hybrid system effluent**	**Hybrid system global removal (%)**
pH	7.2 ± 0.2	–	6.6 ± 0.3	–	6.7 ± 1	–
Alkalinity (mg.L^{-1})	280 ± 34	–	56 ± 33	–	75 ± 4	–
TSS (mg.L^{-1})	45 ± 19	93 ± 11	3.7 ± 4.9	99 ± 3	ND	>99
COD (mg.L^{-1})	586 ± 154	87 ± 8	53 ± 15	80 ± 13	12 ± 9	98 ± 1
TN (mg.L^{-1})	77 ± 15	33 ± 12	52 ± 13	52 ± 23	24.8 ± 11	69 ± 13
NH_4-N (mg.L^{-1})	76 ± 11	63 ± 8	28 ± 7	80 ± 18	6.6 ± 6	91 ± 9
NO_2^--N (mg.L^{-1})	ND	–	1 ± 0.8	–	ND	–
NO_3^-N (mg.L^{-1})	ND	–	25.1 ± 8.6	–	19.4 ± 10	–
PO_4^{3-}P (mg.L^{-1})	32 ± 5	74 ± 5	8.4 ± 2.5	88 ± 5	1 ± 0.5	96 ± 3
Loading rates *n* = 27	**VFCW applied load rate**[a]		**VFCW removal load rate**[a]	**HFCW applied load rate**[b]		**HFCW removal load rate**[b]
TSS (g.m^{-2}.d^{-1})	2.8 ± 1		2.6 ± 1.3	0.1 ± 0.1		0.1 ± 0.1
COD (g.m^{-2}.d^{-1})	39.6 ± 12		36.3 ± 11	1.6 ± 0.8		1.3 ± 0.7
TN (g.m^{-2}.d^{-1})	4.9 ± 1.5		1.5 ± 0.8	1.6 ± 0.5		0.8 ± 0.5
NH_4-N (g.m^{-2}.d^{-1})	4.7 ± 1.5		3.1 ± 1.3	0.8 ± 0.3		0.6 ± 0.3
PO_4^{3-}P (g.m^{-2}.d^{-1})	2.1 ± 0.5		1.5 ± 0.4	0.3 ± 0.2		0.3 ± 0.1

ND, not detectable.

[a] Considering area of 7.5 m^2.

[b] Considering area of 16 m^2.

Thus, the main reason for a falloff in HFCW COD after the 10th operation week was probably due to the greater VFCW efficiencies in carbonaceous organic matter removal. Natural variations of the carbonaceous organic removal efficiency (ranging from 40% to 90%) in CW were frequently reported in previous studies, due to climatic conditions, plant growth stage, and influent quality fluctuations (Zheng *et al.* 2014).

Another performance variation that was noticed was a decline in the efficiency of both VFCW and HFCW close to the 54th week, the moment when the macrophytes were damaged due to an aphid (or more commonly known as plant lice or blackflies) plague. The plague required treatment and, ultimately, the transplant of new macrophytes. Several studies, through the comparison of planted and unplanted CW operated under the same conditions, have already shown that macrophytes usually play a positive role in organic matter removal in CW, mainly due to indirect effects in the microorganisms' community at the rhizosphere (Tanner 2001; Brisson *et al.* 2006). The main affected unit in this study due to macrophyte damage was the HFCW, which presented a decrease of 25% in COD removal during the plague (85 ± 15% to 60 ± 15%, before and after the 54th week of operation). However, despite the reported macrophyte damage, the influent quality fluctuations and the different seasons (daily temperature ranging from 9.8 to 28.8 °C), the hybrid system was able to absorb these variations and to present an average COD removal efficiency of 98 ± 1% (ranging from 93% to 100%), which illustrates the system's resilience. Furthermore, no seasonal effects in the hybrid system performance were noticed during the study. The final effluent had average COD concentrations of 53 ± 15 and 12 ± 9 mg.L^{-1} of COD for VFCW and HFCW, respectively.

Total suspended solids' performance

TSS removal in the hybrid system was very high (>99%) throughout the monitoring. Similarly to the organic matter removal, the TSS removal in VFCW was also affected by

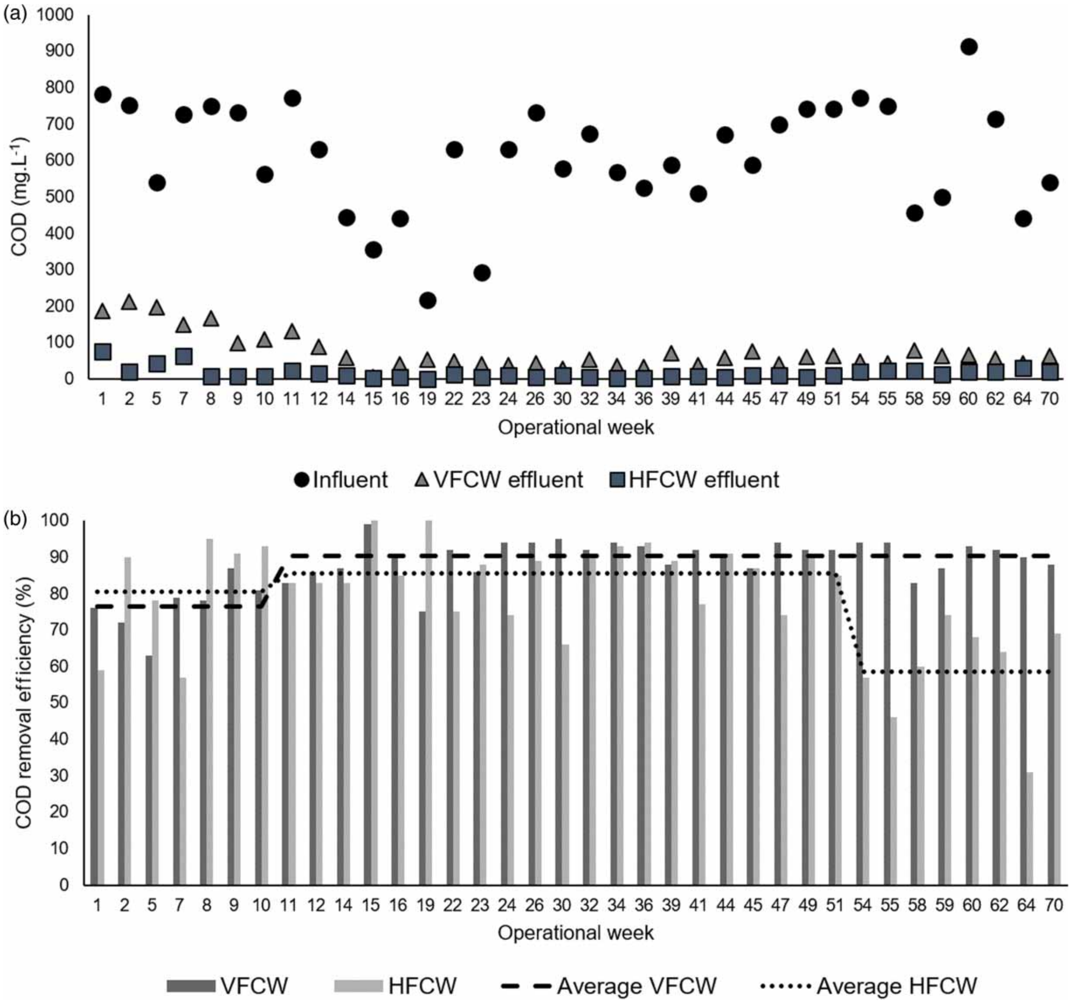


Figure 2 | COD temporal behavior of vertical (VFCW) and horizontal (HFCW) flow constructed wetlands: (a) COD concentration influent and effluent of both wetlands throughout the 70 weeks of monitoring; (b) COD removal efficiency of VFCW and HFCW.

the startup period even though at a smaller magnitude. However, the main modifier on the unit's performance was critical events of intense and long-lasting rains. The VFCW presented TSS removal efficiencies lower than 90% before 10 weeks of operation. After that, the TSS efficiencies went to approximately 100% until the 40th week, when suddenly the performance dropped 51%. The decrease in TSS removal in the VFCW was concurrent with the peak of heavy and long-lasting rains, which had been registered during the 4 previous weeks (Figure 3). These rains were not the most severe registered events. However, it was the only moment when rainfalls stronger than 100 mm.week^{-1} endured for 3 consecutive weeks. This event entailed a total additional input of 385 mm on the VFCW over 4 weeks, which represented an increase of almost 45% input on the VFCW when compared to moments without precipitation (63.2 ± 14 mm.d^{-1}).

The intense rainfall diluted the influent to the lowest TSS concentrations (<20 mgTSS.L^{-1}). Despite that, even with the lowest TSS input, VFCW performance substantially decreased, which might be associated with the washout phenomenon. Evidence that supports the occurrence of the washout was the fact that the highest registered VFCW outflow (7.6 L.min^{-1} or 150% greater than the average daily maximum discharge) was measured at the same time as the VFCW lost more than half of its TSS removal capacity. The washout phenomenon has also been described in a hybrid system VFCW–HFCW–FWS that was suddenly submitted to two times greater HLR due to intense rainfalls

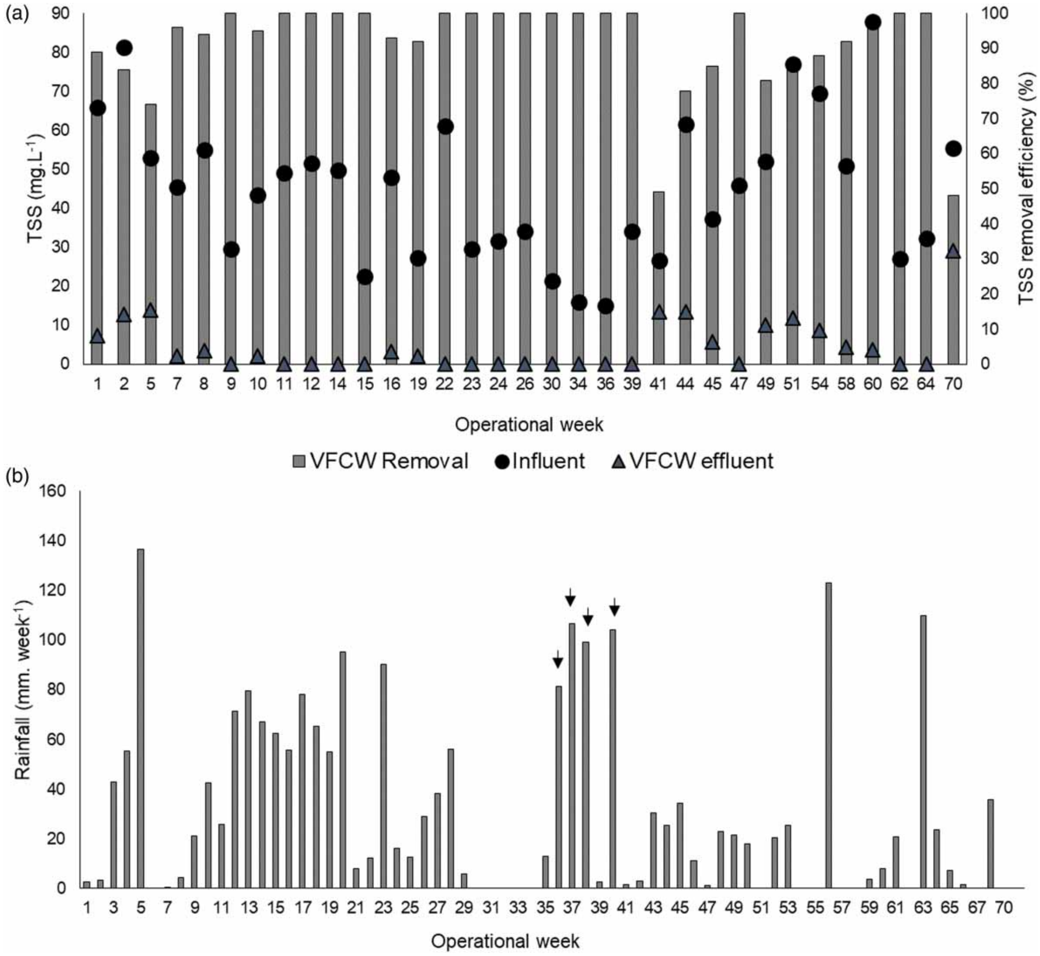


Figure 3 | TSS temporal behavior identified in the vertical flow constructed wetland (VFCW) throughout the 70 weeks of monitoring: (a) influent, effluent and removal efficiency of VFCW; (b) weekly local rainfall throughout monitoring. The heavy and long lasting rainfall event is highlighted in the bottom graph.

(Ávila *et al.* 2013). The authors reported a decrease of COD and TSS removal in both VFCW and HFCW. The VFCW reduced TSS removal from 90% to 65% while the HFCW generated effluents with higher TSS than the influent. In the present study, however, the HFCW did not experience TSS performance loss during intense precipitation events. The maximum TSS concentration in the HFCW effluent was equal to 0.4 mgTSS.L^{-1} and during 74% of the time TSS concentrations were not detectable.

After the critical rainfall event, there was a decrease in rainfall intensity for the following 16 weeks (<35 mm.$week^{-1}$), during which the VFCW was able to progressively recover its previous TSS removal performance. Ultimately, the VFCW achieved the previous 100% efficiency at the 70th week.

Nitrogen transformations and removal

Throughout the monitoring, the hybrid system was able to remove 91 ± 9% of NH_4^+-N and 69 ± 13% of TN. Each VFCW and HFCW had different roles in nitrogen transformations and removal in the hybrid system. In regard to the VFCW, the average NH_4^+-N removal was 68 ± 8%, whereas TN removal was only 33 ± 12%. In this modality of CW, it is already known that nitrification is the main mechanism linked to nitrogen transformation, while TN removal is limited (from 40% to 50%) due to the low denitrification potential (Vymazal 2007). In regard to fluctuations throughout the monitoring period, no clear temporal behavior of TN and NH_4^+-N removal and NO_3^-N production were identified. However, it was noticeable that the moments with the smaller NO_3^-N productions were concurrent with the higher NO_2^-N concentrations in the VFCW effluent (Figure 4(a)). The presence of nitrite in the effluent of a wastewater biological treatment plant may indicate that nitrification was not complete, while it is known that biological nitrogen consumption varies positively with temperature (USEPA 1983). Pearson's linear correlations were detected, which suggests that partial nitrification occurred in the VFCW, since greater amounts of NH_4^+-N and smaller of NO_2^-N were measured simultaneously and usually during moments with warmer air temperatures. The Pearson's linear correlations found are: NO_2^-N VFCW effluent and air temperature (−0.9917); NO_2^-N VFCW effluent and NH_4^+-N VFCW effluent (+0.7170); NH_4^+-N VFCW effluent and air temperature (−0.7200); NH_4^+-N VFCW effluent and VFCW pH effluent (+0.7493); and NH_4^+-N VFCW effluent and VFCW effluent alkalinity (+0.6609).

In regard to the HFCW, the unit presented low denitrification performance, which resulted in significant amounts of nitrate (19.4 ± 10 $mgNO_3^-N.L^{-1}$) in the final effluent. The limited nitrogen removal was probably due to the low C:N ratio in the HFCW influent (1:1 [COD:TN]), since some studies have already shown that low C:N ratios compromise the denitrification process (Lu *et al.* 2009; Ding *et al.* 2014). On the other hand, this might have favored ammonium consumption in the rhizosphere, where nitrifying bacteria can be established due to higher dissolved oxygen concentrations (Reddy & Patrick 1984; Bothe *et al.* 2000), and have their activity enhanced when submitted to low C:N (Liu *et al.* 2013). The average removal of NH_4^+-N in the HFCW was 80 ± 18%.

The combination of these processes might have disfavored denitrification in the HFCW and enhanced nitrification, which resulted in the generation of a final effluent with low NH_4^+-N. Ammonia levels remained below 10 $mgNH_4^+$-$N.L^{-1}$ during 64% of the monitoring (Figure 4(b)). It could be noticed that after the 18th week of operation the HFCW started to show effluents below 10 $mgNH_4^+$-$N.L^{-1}$. The NH_4^+-N removal efficiency increase after the 18th week may be related to a lower COD input on the HFCW after the 10th week (Figure 2). After that moment, the autotrophic nitrifying community at the rhizosphere may have started its establishment due to lower competition with heterotrophic bacteria since carbon was less available. The development of the nitrifiers may have culminated 8 weeks later, when the lowest NH_4^+-N concentrations were measured in the HFCW effluent. This time gap agrees with the required time of 9 weeks in order to observe nitrifying community establishment in VFCW and consequent ammonium consumption (Santos 2015).

The low NH_4^+-N concentrations remained stable from the 18th to the 50th week. After that, the NH_4^+-N removal efficiency decreased, which resulted in effluent concentrations over 10 mg NH_4^+-$N.L^{-1}$. The efficiency loss was close to the aphid plague at the 54th week. It may be possible that the damage caused by the plant lice on the macrophytes compromised plant activity, both in oxygen supply and nutrients uptake. Brix *et al.* (2002) state that nitrogen plant uptake in CW prioritizes ammonia ions rather than the oxidized nitrate or nitrite forms. After treating the macrophytes with tobacco solution (300 g of tobacco rope mixed in 1 L alcohol for 2 days, which was then diluted in 5 L of water) and transplanting new plants, the NH_4^+-N removal efficiency rose towards the efficiencies registered between weeks 20 and 50. The HFCW effluent achieved NH_4^+-N concentrations below 10 mg.NH_4^+-$N.L^{-1}$ again after the 60th operational week.

The aphid plague may also have disfavored TN and NO_3^-N removal in the HFCW. The literature also indicates an increment on CW performance in nitrogen removal due to plant activity (plant assimilation, plant oxygen input, and root release of exudates that favors microorganism activity) (Brix *et al.* 2002; Brisson *et al.* 2006; Caselles-Osorio *et al.* 2017).

The low NO_3^-N removal in the HFCW observed during the monitoring led to an operation strategy of limiting the HFCW pruning after the 24th week, in order to let the macrophytes reach senescence, dry, and then return part of their carbon to the bed media. Some studies have already tested the reintroduction of carbon from the leaf tissue of the macrophytes, with the aim of increasing denitrification rates. Gersberg *et al.* (1984) were pioneering researchers on denitrification of CW that received low BOD_5 and high NO_3^-N. Among the different strategies that the authors applied, the placement of trimmed leaves over the bed media resulted in an increase of 9% to 89% on TN removal. The placement of trimmed leaves on the bed media could reintroduce not only carbon but also nutrients that had been previously assimilated by the plant, since nutrient storage in leaf tissue has already been reported in the CW

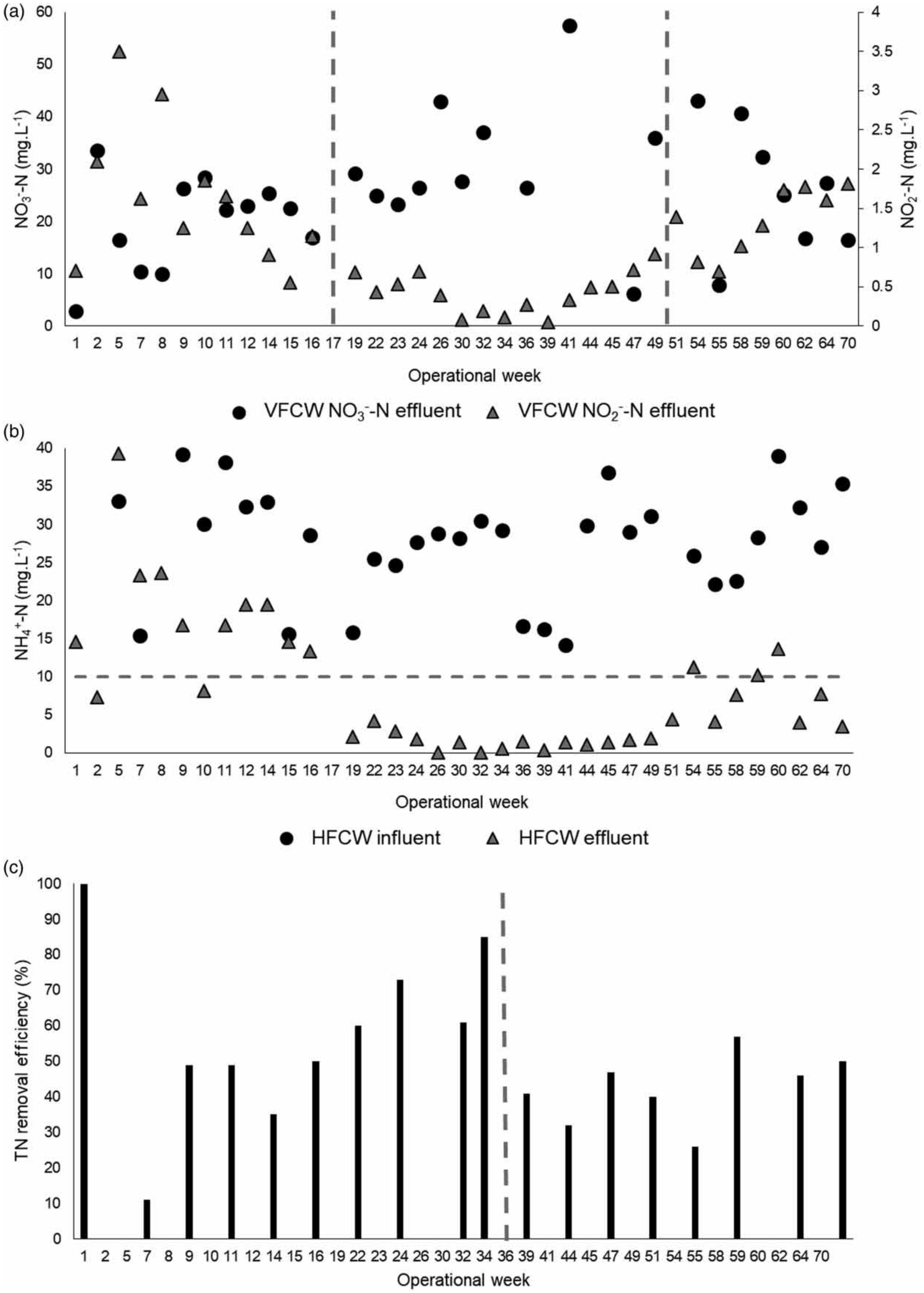


Figure 4 | Behavior of the different nitrogen fractions identified in the vertical (VFCW) and horizontal (HFCW) flow constructed wetlands: (a) temporal simultaneity of NO_3^-N decrease (left axis) and NO_2^-N increase (right axis) in VFCW effluent; (b) HFCW NH_4^+-N effluent concentration decrease after the 18th week and increase close to the aphid plague observed in the 54th week; (c) HFCW TN removal efficiency decrease after the 36th operational week.

literature (Zheng *et al.* 2015). Controversially, during the senescence period, crops direct the nutrients in leaf tissues to the rhizosphere as a metabolic adaptation (Thomas & Ougham 2015), which could then be interesting since the dry leaves would contain mainly carbon. In that way, the pruning limitation strategy was adopted to verify whether unharvesting the HFCW would contribute to NO_3^-N and TN removal in the HFCW. However, the strategy was not successful. After the 36th week of operation the TN removal efficiency dropped (Figure 4(c)). This decrease could be related to an increase in NO_3^-N input at this time, together with a decrease of plant activity due to the combination of unharvesting and aphid plague. In that way, it is suggested that pruning be continuously done in the HFCW.

Phosphorus orthophosphate performance

The hybrid system presented an excellent $PO_4^{3-}P$ removal throughout the monitoring (96 ± 3%). The removal rate was stable during the time in both the VFCW and HFCW, and presented a slight decrease in performance after the 44th and 50th week of operation, respectively. Despite this, the final hybrid effluent was always lower than 2 mg $PO_4^{3-}P.L^{-1}$. The VFCW generated an effluent with less than 10 mg $PO_4^{3-}P.L^{-1}$ (average of 7 ± 2 mg $PO_4^{3-}P.L^{-1}$) until the 44th week. Afterwards, the effluent rose to 10 mg $PO_4^{3-}P.L^{-1}$ (average of 10.6 ± 1.5 mg $PO_4^{3-}P.L^{-1}$) until the end of the monitoring. Even with the rise of $PO_4^{3-}P$ in the VFCW effluent, the unit had always presented efficiencies greater than 60% (Figure 5).

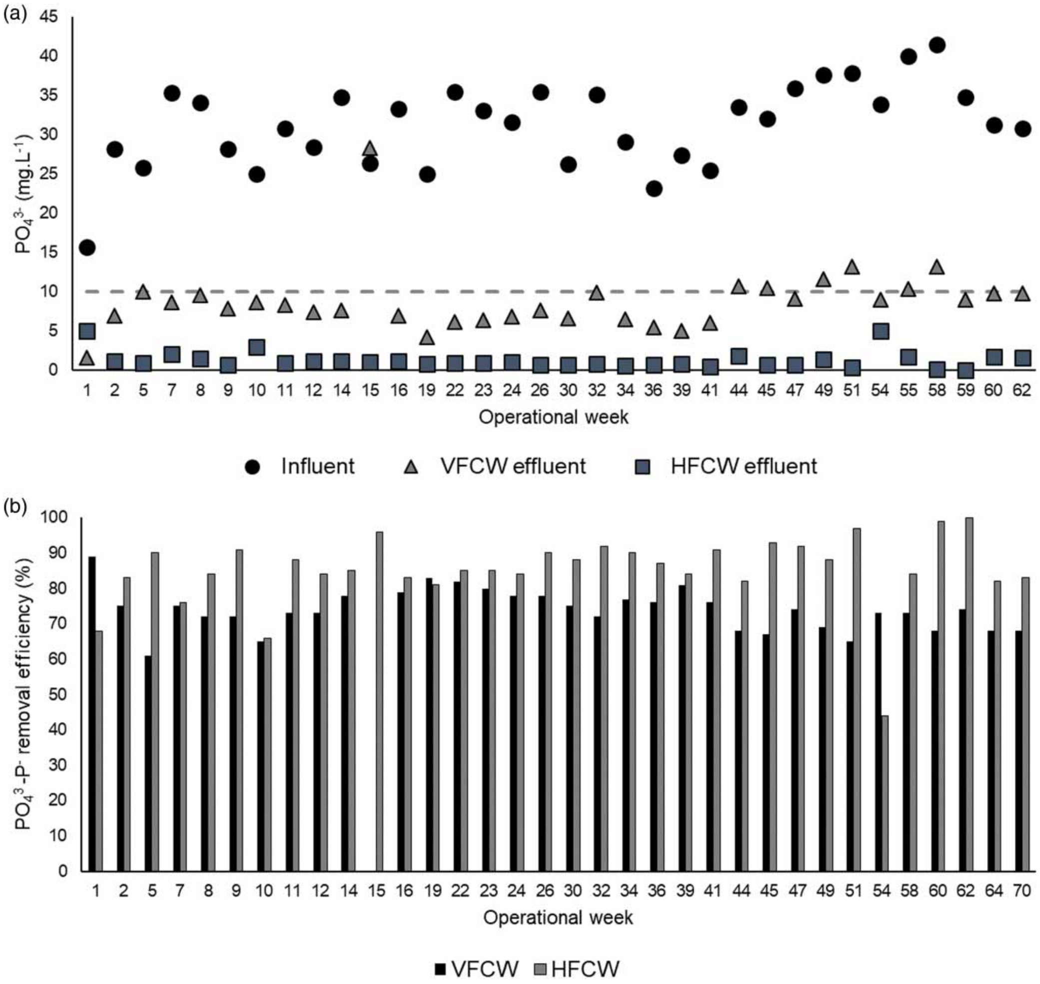


Figure 5 | Temporal behavior of $PO_4^{3-}P$ influent and effluent of vertical (VFCW) and horizontal (HFCW) flow constructed wetlands: (a) $PO_4^{3-}P$ influent and effluent concentrations of VFCW and HFCW; (b) removal efficiencies of VFCW and HFCW.

On the other hand, the performance drop on the HFCW and PO_4^{3-}-P removal was not as noticeable as in the VFCW. It was identified as a slight tendency of PO_4^{3-}-P increase in the HFCW effluent after the 50th operational week. This increase may be associated with the greater PO_4^{3-}-P loads on the HFCW, due to VFCW performance loss, or with the decreasing capacity of the bed media to adsorb phosphorus throughout operation. However, it must be considered that these results refer only to the first 70 weeks of operation of the CW units. Phosphorus removal is expected to reduce over time in this system, due to the fact that adsorption is the main pathway by which phosphorus is removed in CW (Brix *et al.* 2001), while the plants' uptake and the microorganisms' removal represent a smaller fraction of this nutrient removal (Kadlec & Wallace 2009). In this way, since adsorption is a function of the capacity of the bed media to hold cations and will saturate over time, phosphorus removal decrease throughout the operation is likely to happen.

CONCLUSIONS

This study evaluated the treatment performance of a hybrid system (VFCW–HFCW) in southern Brazil during the first 70 weeks of operation. Based on this, one can draw the following conclusions.

The initial period of 10 weeks represented a cornerstone for the upgrade of the hybrid system COD and TSS removal performance, especially in the case of the VFCW unit, where treatment performance increased after this period, from 77% to 90% for COD and >90% to 100% for TSS. Therefore, according to our results, practitioners should expect a startup period, after which the system's performance should increase.

Extreme long-lasting rains negatively affected primarily the VFCW's TSS removal. After 3 consecutive weeks of intense rainfalls (greater than 100 mm.week^{-1}) the removal efficiency dropped 51%. However, performance gradually increased after the extreme event. The VFCW was able to reach maximum performance again 4 weeks later. This exemplifies the system's resilience to recover its previous performance after extreme weather events.

The aphid plague that occurred affected mostly the HFCW's performance rather than the VFCW's performance. The HFCW's removal efficiency decreased 25%, 13%, and 10% COD, NH_4-N, and TN, respectively.

A low denitrification in the HFCW was observed throughout the monitoring due to low influent C:N. On the other hand, the low influent C:N seemed to favor NH_4^+-N removal in the HFCW. This fact indicates that the final hybrid system effluent could be potentially interesting for agricultural purposes.

In general, the hybrid system showed average removal efficiencies greater than 90% for COD, TSS, NH_4^+-N, and PO_3^-P. TN removal was in the order of 69%. The monitored VFCW–HFCW hybrid system presented resilience even though extreme rainfall events and aphid plagues occurred during the monitoring period. Furthermore, throughout the whole monitoring, the hybrid system always generated an effluent that was suitable to be discharged into sensible environments, according to Brazilian national and state regulations.

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