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Performance of modified first-stage French Vertical Flow Constructed Wetlands under extreme operational conditions

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ABSTRACT

Operation conditions considerably affect the removal efficiency of wastewater treatment systems, and yet we still lack data on how these systems function under extreme dilution rates and climatic conditions at high altitudes. Here, we applied two modified First-Stage French Vertical Flow Constructed Wetlands (FS-FVFCWs) for sewage treatment in Northern Tropical Andes. Specifically, within 18 months, we conducted a pilot-scale experiment at two hydraulic loading rates (HLRs) of 0.94 and 0.56 m d^{-1}, representing 2.5 and 1.5 times the recommended design values, with two different feeding/resting periods to investigate the impact of HLRs and operational strategy on system performance. We found that chemical oxygen demand (COD) and total suspended solids (TSS) removal was satisfactory, with average values of 53 ± 18 and 69 ± 16%, respectively. Moreover, reducing HLRs resulted in higher removal efficiency for COD, from 46 ± 15 to 64 ± 15%, but had no impact on TSS removal, with 3 days of feeding and 6 days of resting. For an equal time of feeding and resting, COD and TSS removals were not affected by the modified HLR. These findings suggest that high HLRs can be applied to FS-FVFCW without compromising the system operation and obtaining satisfactory results, leading to opportunities to reduce areas and costs.

Key words: combined sewer wastewater, First-Stage French Vertical Flow Constructed Wetlands, hydraulic loading rate, northern tropical andes, operation conditions

HIGHLIGHTS

- The FS-FVFCW has a satisfactory performance with HLRs higher than the recommended ones.
- Increasing HLRs has an impact on COD removal but does not have any impact on TSS removal.
- Significant reduction in the land requirement for the FS-FVFCW can be achieved when treating diluted wastewater.

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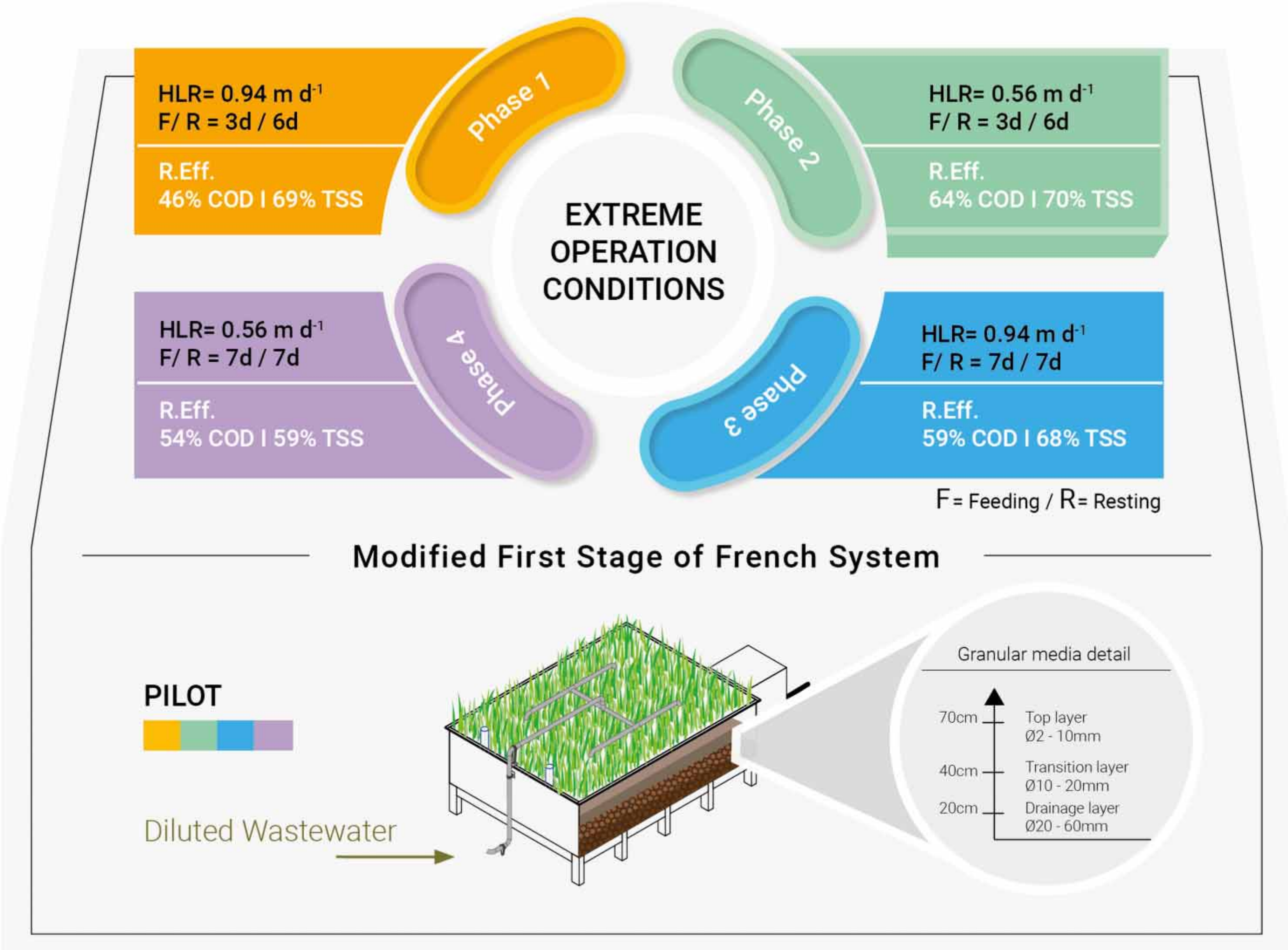
GRAPHICAL ABSTRACT



1. INTRODUCTION

French Vertical Flow Constructed Wetlands (FVFCWs) are a nature-based system that have the benefits of constructed wetlands for wastewater treatment, such as low establishment costs, robustness, and easy operation and maintenance. On top of these advantages, FVFCWs can treat sludge and wastewater in a single step, without the use of primary treatment, such as a septic tank. Specifically, FVFCWs have positive effects on sludge accumulation because of the feeding of unsettled wastewater. This sludge deposit layer that is formed improves filtration efficiency for solids removal, water retention time, and thus treatment performances and water distribution onto the filter's surface. Furthermore, the sludge layer with sufficient thickness is the place where most of the biological activity takes place, including the degradation of organic matter (Molle 2014). The shifting between feeding and resting phases, including hydraulic and organic loads, is fundamental as they directly affect treatment performance and deposit mineralisation, otherwise, ponding and surface clogging would occur (Decezaro *et al.* 2019; Trein *et al.* 2020). Because of these characteristics, FVFCWs hold immense potential in areas where technical expertise, economic resources, and sludge management options are limited. This makes them particularly suitable for small rural communities with populations of less than 2,000 inhabitants (Molle *et al.* 2005; Lombard-Latune *et al.* 2020)

The classical design of the French System comprises two stages in series (footprint of 2 m^2 Pe^{-1}), in which three units operate in the first stage (1.2 m^2 Pe^{-1}) and two units in the second stage (0.8 m^2 Pe^{-1}). The first stage (FS-FVFCW) receives the raw wastewater that percolates through the porous media and consequently forms a sludge deposit layer on the top of the bed. The second stage receives the effluent from the first stage to treat wastewater up to full nitrification (Molle 2014). First stage units receive a design load during the feeding phase that lasts for 3.5 days and then are rested for 7 days, while second stage

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units are fed and rested for the same amount of time. Over the past years, a compact version of the classical French system has been used, consisting only of the first stage with a footprint of 1.2 m^2 Pe^{-1} (Paing *et al.* 2015). Another notable example is the French system for tropical climates which is more compact and consists of only two parallel filters in a single stage with a footprint of 0.8 m^2 Pe^{-1} (Lombard Latune & Molle 2017). This design has been used in the French Overseas Territories (Molle *et al.* 2015) and Brazil (Manjate *et al.* 2015).

Molle *et al.* (2005) presented the guidelines for designing classical French systems, which recommend the use of FS-FVFCWs to treat raw wastewater from separate sewage collection networks. The design values for these systems include organic loading rate (OLR) of around 300 g chemical oxygen demand (COD) m^{-2} d^{-1}, total suspended solids (TSS) of 150 g m^{-2} d^{-1}, and hydraulic loading rate (HLR) of 0.37 m d^{-1}, which corresponds to the footprint of 1.2 m^2 PE^{-1}. For tropical areas, the recommended values are 350 g COD m^{-2} d^{-1} and an HLR $<$0.75 m d^{-1} on the filter in operation (Lombard Latune & Molle 2017). Batch volume and frequency are also important considerations for these systems. Specifically, related to the instantaneous surface HLR during each pulse, the batch volume should be higher than 0.5 m^3 m^{-2} h^{-1} while the water level should be between 2 and 5 cm in the filter in operation for even water distribution (Dotro *et al.* 2017). Batch frequency can be determined based on the water level calculated by filter area and daily flow (García Zumalacarregui & von Sperling 2018). In the first stage of the classic design, Morvannou *et al.* (2015) found mean efficiency values of 77 and 83% for COD and TSS, respectively, with an average HLR of 0.37 m d^{-1}. Molle *et al.* (2005) reported mean efficiency values of 79 and 86% for COD and TSS, respectively, with HLRs below 0.6 m d^{-1}. Additionally, Paing *et al.* (2015) mentioned that COD removal performance decreased and exhibited high variability when the HLRs exceeded 0.6 m d^{-1}. Higher HLRs than those mentioned could result in system efficiencies falling below 80%, depending on the hydraulic load (Molle *et al.* 2006).

Despite the benefits of FVFCWs, there remain limited studies on their performance under various conditions, including both operation strategy and climatic conditions. Most studies conducted the systems with recommended values and only two of them were in Latin America, Brazil, and French Guyana (warm climates) (Rodriguez-Dominguez *et al.* 2020). In effect, no data on their performance have been reported at high altitudes, particularly in the Northern Tropical Andes which is uniquely characterised by strong solar radiation, large daily temperature variation, and strong winds (Ho *et al.* 2018).

Building on these perspectives, we installed and operated – for the first time – a pilot-scale-modified FS-FVFCW to treat raw wastewater derived from a combined sewer system at the altitude of 2,500 m a.s.l. in Cuenca, Ecuador (Northern Tropical Andes). Specifically, we tested the performance of the two pilots over 18 months at two operation conditions of HLRs of 0.94 and 0.56 m d^{-1} in order to investigate the possibilities that FS-FVFCW (i) can be applied at highlands and (ii) can cope with high HLRs while remaining satisfactory efficiencies.

2. MATERIALS AND METHODS

2.1. Experimental setup

Two pilot-scale-modified FS-FVFCWs were installed at Ucubamba Wastewater Treatment Plant (WWTP) in Cuenca located in the south Andes of Ecuador (2°52′15.1″S, 78°56′30.8″ W). The region has an annual average temperature of 16.3 °C and average annual rainfall of 879 mm with the rainy season occurring from the middle of February until the beginning of July and from the second half of September until the first 2 weeks of November. The dry season occurs the rest of the year (Jerves-Cobo *et al.* 2020).

The pilots had a superficial area of 9.81 m^2 with a length to width ratio of 1.3:1 and a depth of 1 m filled with granular media of 0.7 m (Figure 1). From the top to the bottom, the filter media consisted of three layers: (1) 30 cm of small gravel (⌀ 2–10 mm); (2) 20 cm of middle gravel (⌀10–20 mm); and (3) 20 cm for the drainage layer (⌀ 20–60 mm). This design is a modified configuration of the first stage of the French System according to Molle *et al.* (2005). The planted vegetation was *Lolium perenne*, a common grass specie that grows easily in the local climate.

The influent of the pilots was the raw wastewater from the combined sewer network of Cuenca City. The wastewater passed through coarse screening and grit removal before being discharged to the wetland pilots. Feeding was carried out in batches every hour, amounting to 24 batches per day, during 18 months, from January 2021 to July 2022. During this period, the pilots underwent four phases varying HLR and feeding and resting periods as follows:

- First phase: HLR of 0.94 m d^{-1}, 3 days of feeding with 6 days of resting (six months)
- Second phase: HLR of 0.56 m d^{-1}, 3 days of feeding with 6 days of resting (four months)
- Third phase: HLR of 0.94 m d^{-1}, 7 days of feeding with 7 days of resting (three months)
- Fourth phase: HLR of 0.56 m d^{-1}, 7 days of feeding with 7 days of resting (five months)

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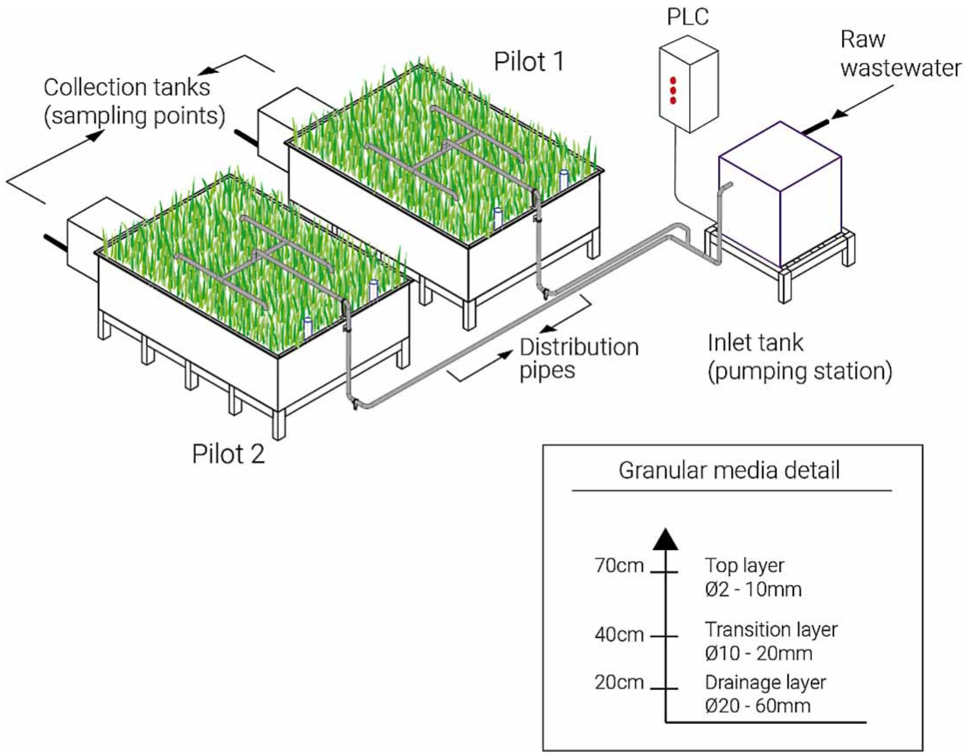

Figure 1 | Schematic overview of the pilot-scale-modified FS-FVFCWs.

Note that the applied HLRs of 0.94 and 0.56 m d^{-1} were 2.5 times and 1.5 times higher than the recommended value of 0.37 m d^{-1}, respectively. A water level sensor and a Programmable Logic Controller (LOGO! 230RC Siemens) were used to control the volume of raw wastewater in the inlet tank and maintain stable HLRs. In line with the recommendation of Dotro *et al.* (2017) that the instantaneous surface HLR should be higher than 0.5 m^3 m^{-2} h^{-1}, for the HLR of 0.94 m d^{-1}, a volume of 0.38 m^3 was discharged during 2.52 min and for the HLR of 0.56 m d^{-1}, the volume discharged was 0.23 m^3 during 1.50 min, both of them resulting in an instantaneous surface HLR of 0.93 m^3 m^{-2} h^{-1}.

In the first and second phases, the pilots rested for the double time of the feeding period to allow for aerobic conditions within the filter, let the sludge deposit layer on the top to mineralise and control the growth of attached biomass on the filter media. In the third and fourth phases, we tested whether we could reduce the total required area by applying only two parallel filters with equal time for feeding and resting, based on experiences from warmer climates.

2.2. Operation monitoring

The monitoring of the pilots started after four months of a start-up phase which was conducted to ensure the establishment of the vegetation and microorganisms in the filter media. Grab and flow composite samples were collected in the influent and effluent of the pilots during the morning batch (08.00 h) on the second day of each feeding period. The samples were then analysed for TSS, COD, and BOD_5. COD and TSS were analysed following the *Standard Methods for the Examination of Water and Wastewater* (APHA/AWWA/WEF 2012) while BOD_5 was analysed using a respirometric system (Lovibond BD 600).

Meteorological data were obtained from Ucubamba meteorological station located within the Ucubamba WWTP. Average air temperature and precipitation were recorded every 5 min in °C and mm, respectively, throughout the investigation period. In order to obtain representative values for the statistical analysis, the mean temperature was computed using the values recorded during the hour of the sampling batch, i.e. from 8 am to 9 am. Precipitation was grouped into three variables: the total precipitation during the hour of the sampling batch (precipitation batch), the total precipitation during the day before the sample was taken (precipitation 1 day) and the total precipitation during the period that each wetland was resting before the next feeding batch (precipitation rest).

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2.3. Statistical analysis

To investigate the effects of HLRs, OLRs and operational strategies on the removal efficiencies of the FS-VCW pilots, the experimental results were statistically analysed using R software (Version 2022.12.0 + 353). Since the data were non-normally distributed and independent (time series data), non-parametric tests were applied after verifying the necessary assumptions. Specifically, the Kruskal–Wallis test followed by Bonferroni–Dunn test was applied for comparison between the four phases. The Mann–Whitney *U* test was used to compare the COD and TSS concentrations of the influent between the two pilots, as well as to investigate the effect of HLR, OLR, air temperature, precipitation and operational strategies on removal efficiencies. In addition, Spearman rank correlation was calculated between the variables and the removal efficiencies. The *p-value* was considered significant at 0.05.

3. RESULTS AND DISCUSSION

3.1. Characteristics of the raw and treated sewage

Figure 2 presents the mean characteristics of the influent and effluent during the sampling period, which shows the high variations of COD and TSS concentrations. The predominant low values demonstrated the dilution of raw wastewater which can

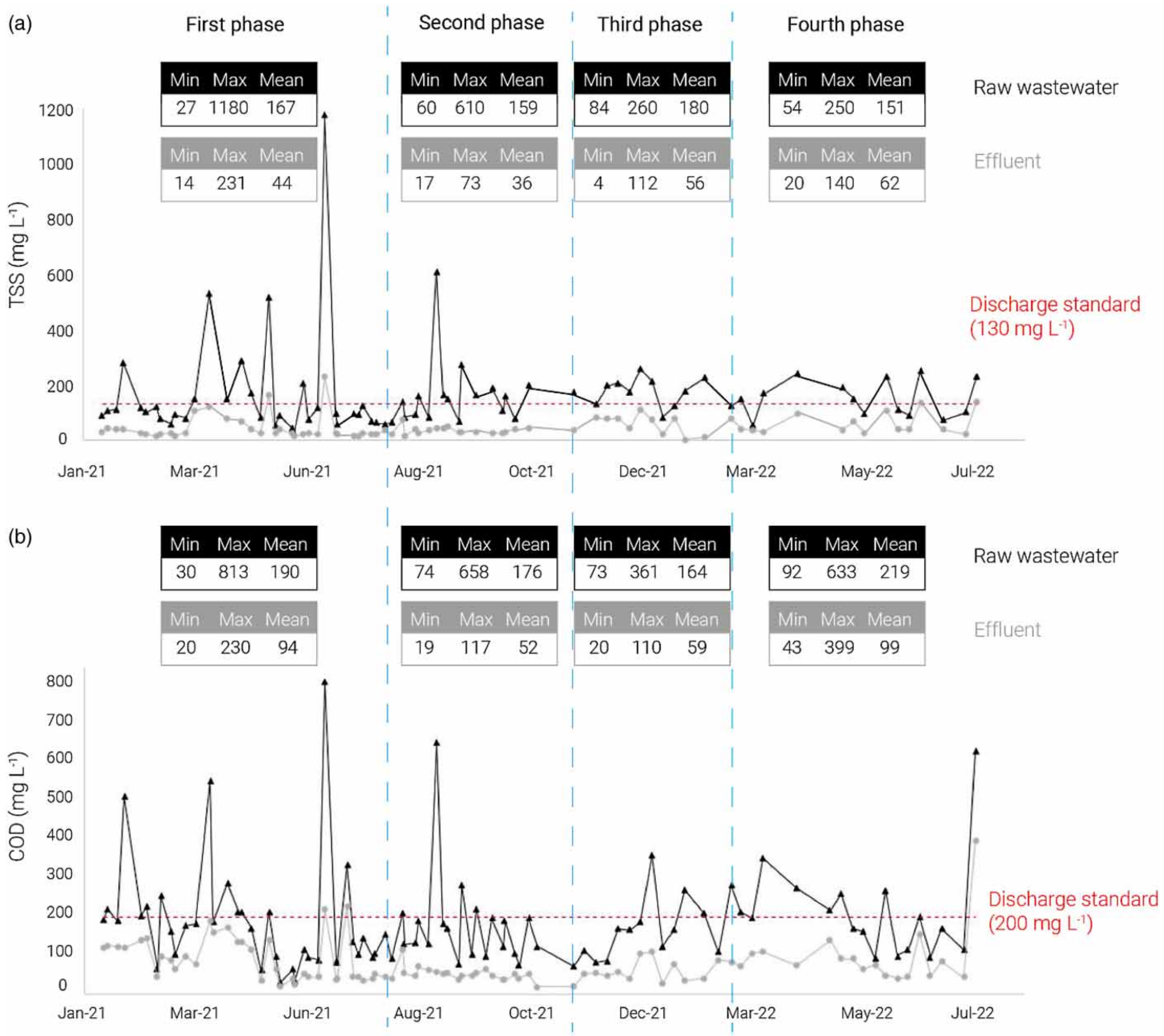

Figure 2 | Influent and effluent concentrations of (a) TSS ($n = 77$) and (b) COD ($n = 89$) during the four experimental phases (from January 2021 to July 2022).

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be explained by the type of combined sewer network. The presence of high peak values can be attributed to discharges of the industrial park and municipal slaughterhouse that flow into the same sewer system. Note that mean COD and TSS were lower than the common values of 260–480 mg L^{-1} of COD and 270–550 mg L^{-1} of TSS from combined wastewater (Tchobanoglous *et al.* 2014), which could be influenced by the conveyance in the sewer system. According to Gao *et al.* (2023), approximately 3–32% of the COD can be lost during conveyance depending on the length, slope, diameter, and other parameters. The raw wastewater presented here arrives at the WWTP from a combined sewer network with the furthest point located around 40 km away. It is worth noting that the mean ratio TSS/COD was stable at around 0.9, which is higher than the typical value of 0.5 in separate sewer networks. This reflects the design recommendations of Molle *et al.* (2005) for FVFCW.

The effluents of the pilots complied with the Ecuadorian discharge standards to freshwater bodies despite the wide variation in influent concentrations, with COD of 200 mg L^{-1} and TSS of 130 mg L^{-1} (Figure 2). This indicates the robustness of the pilots as they can cope with high fluctuation in the influent concentrations. Mean removal efficiencies of 53 $\pm$ 18, 69 $\pm$ 16, and 42 $\pm$ 15% for COD, TSS, and BOD_5, respectively, were calculated. As expected, those values are relatively low compared to those of the mature systems operating with lower HLRs, i.e. 77 and 83% for COD and TSS (Morvannou *et al.* 2015). Another factor that may have influenced the achieved removal efficiencies is the size of the granular media used in the pilots (Figure 1). The system under study is a modification of the classical one, and larger granular media with wider ranges were used.

The mean BOD_5 was 101 mg L^{-1} in the raw wastewater, and 45 mg L^{-1} in the effluent. The BOD_5/COD ratio for both the raw wastewater (0.49) and effluent (0.52) was higher than 0.4 indicating a high biodegradable fraction (Tchobanoglous *et al.* 2014). There was a slight increase in the BOD_5/COD ratio in the effluent, which could be explained by the excess plant biomass in wetland systems that could be exported out of the wetland and measured as levels of BOD, TSS, and nutrients (Kadlec & Wallace 2009).

3.2. Treatment phases

Table 1 presents the *p*-values obtained from Kruskal–Wallis test (adjusted using the Bonferroni correction) when investigating the difference between the relevant variables (COD and TSS removal, OLRs and Precipitation during the rest period) for the different phases applied. The results showed strong evidence of a difference in COD removal and OLR presented as g COD m^{-2} d^{-1} only between the first and second phases. However, for TSS removal there was not a significant difference between any of the phases. For OLR presented as g TSS m^{-2} d^{-1} there was a difference between the second and third phases, and the third and fourth phases. Organic loads were not controlled during the experimental setup, only hydraulic ones, thus the TSS and COD OLRs depended solely on the raw wastewater that entered the WWTP.

The experimental phases did not coincide with the rainy or dry season. The first, second and third phases were carried out during both, the rainy and dry seasons, but the fourth phase was executed during the months of the rainy season. According to the results, only precipitation during the rest period had a difference for phases 2–3 and 2–4, while the other two variables of precipitation (1 day before and during the batch) did not show any significant difference between the phases.

Table 1 | Comparing COD removal, TSS removal, OLRs, and precipitation using *p*-values of the Kruskal–Wallis test between the four treatment phases

	Variables				
Phase	**COD removal**	**TSS removal**	**OLR (COD g m^{-2} d^{-1})**	**OLR (TSS g m^{-2} d^{-1})**	**Precipitation rest**
1–2	<0.001***	0.71	<0.01**	0.36	0.92
1–3	0.067	0.74	0.98	0.058	0.072
1–4	0.45	0.31	0.67	0.18	0.11
2–3	0.51	0.56	0.076	<0.001***	<0.01**
2–4	0.54	0.24	0.20	0.70	<0.01**
3–4	0.39	0.21	0.20	<0.01**	0.075

: *p*-value <0.01 (Highly statistically significant); *: *p*-value < 0.001 (Extremely statistically significant).

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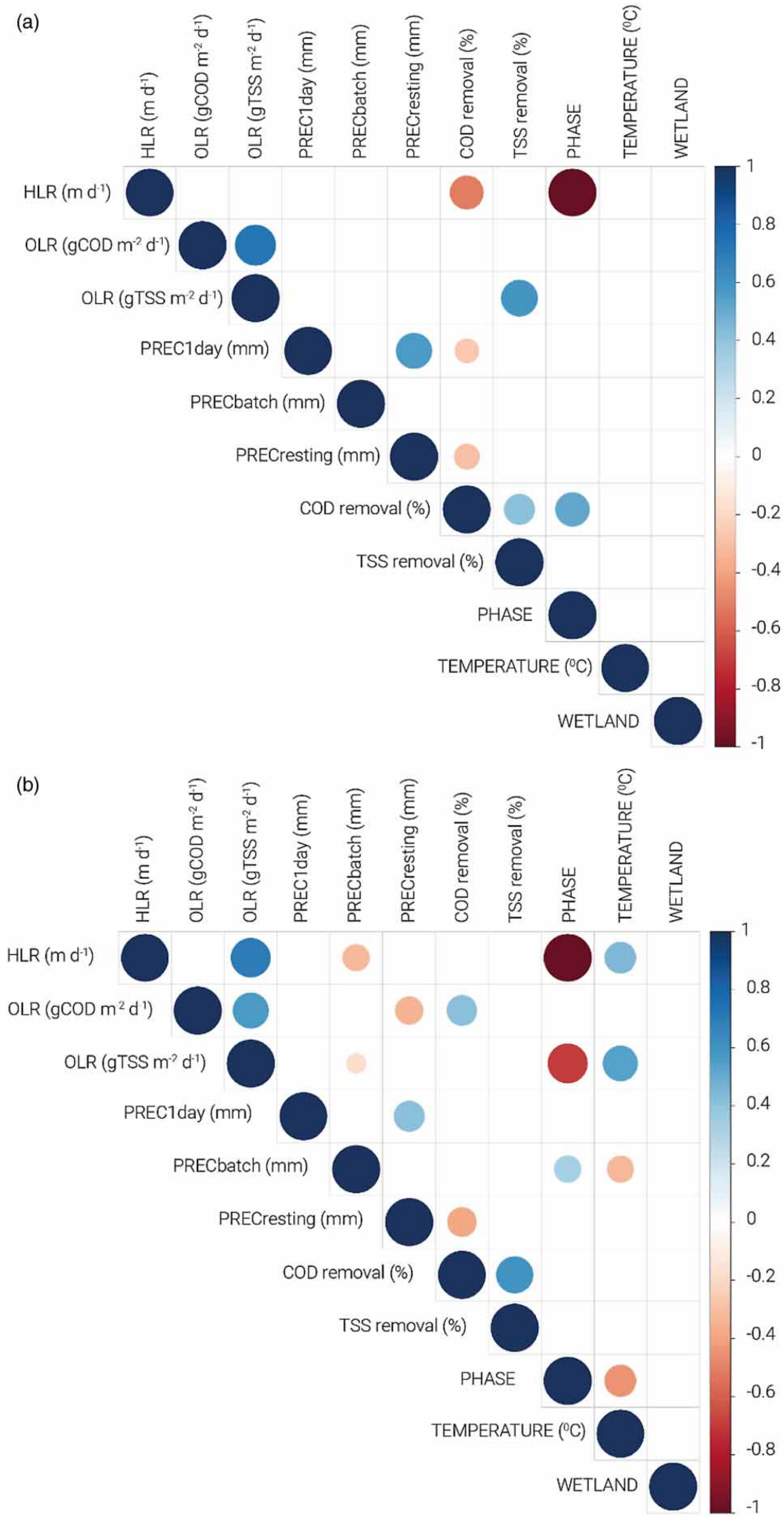

Figure 3 | Graphical display of the correlation matrix between all the variables analysed (a) for 3 days of feeding and 6 days of resting and (b) for 7 days of feeding and 7 days of resting. *Note*: insignificant correlations (p-value < 0.05) are left blank.

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3.3. Influence of main parameters on treatment performance

Figure 3 shows the correlation of the main variables analysed for each operational strategy. The variable wetland did not exhibit any significant correlation with the other variables, suggesting that both wetlands performed similarly during the experiments. The following paragraphs analyse the other variables that showed any kind of correlation.

3.3.1. Hydraulic loading rate

During the four experimental phases, different values of treatment performance were obtained as shown in Figure 4. The best performance for the evaluated parameters (COD and TSS) was achieved during the second phase (HLR of 0.56 m d^{-1}, 3 days of feeding with 6 days of resting). These results suggest that higher HLRs can be used in this type of wetlands but maintain the design recommendations of 3.5 days (or less) of feeding time and doubling the resting time, albeit with a slight reduction in the treatment efficiency. During the third phase, the wetlands were operating at limited conditions, i.e. highest HLR and equal feeding and resting periods, and the efficiencies obtained were mostly over 40%. Even though the wetlands kept removing pollutants under these conditions, it was observed in the field that the experimental units started clogging, as the volume of water during a batch incompletely infiltrate before the next batch (Pucher & Langergraber 2019).

During the fourth phase, the pilots continued to function but with lower treatment performance in comparison to the previous phases. According to the design parameters for the classical system, it is recommended to have an optimal feeding period of 3.5 days (Molle *et al.* 2005). Furthermore, in order to maintain satisfactory system performance, it is advised to adapt the feeding system for hydraulic overloads, allowing longer intervals between batches (Molle *et al.* 2006). Similarly, Rizzo *et al.* (2020) propose that in FVFCWs treating combined sewer overflow, the feeding and resting periods should be switched on a monthly basis to ensure uniform sediment distribution and prevent clogging.

In our case, we treated combined sewer wastewater with a longer feeding time (7 days) and shorter resting periods, which resulted in a rapid accumulation of sediments in a short timeframe. This excessive sediment accumulation led to the degradation of the system's performance, with an additional 3 cm of sediment accumulation observed at the end of the third phase, while Molle (2014) mentions 2.5 cm $year^{-1}$ under nominal load conditions. To optimise the system, the thickness of the sludge layer should be sufficiently thick for bacterial mineralisation while thin enough to avoid ponding and surface clogging (Trein *et al.* 2020). During the first phase, the sludge layer was not well formed, with only around 1 cm of sludge near the inlets, which likely impacted the efficiencies, especially for COD, which showed the lowest removal. In the last two phases, the deposit layer increased but the resting time was insufficient for mineralisation resulting in loss of efficiency as well.

When comparing the two applied HLRs, the Mann–Whitney U test showed a significant difference in COD removal (p-value < 0.01) in contrast to no significant difference in TSS removal (p-value $= 0.92$). On the other hand, we found no significant difference in both COD and TSS removal when comparing the two feeding and resting strategies (p-value $= 0.37$, p-value $= 0.28$, respectively). This implies that the decrease in removal efficiencies in the third and fourth phases compared to the second phase was due to the reduction in resting time. This fact is also reflected in Figure 3(b), which shows no significant correlation between HLR and COD removal during these phases.

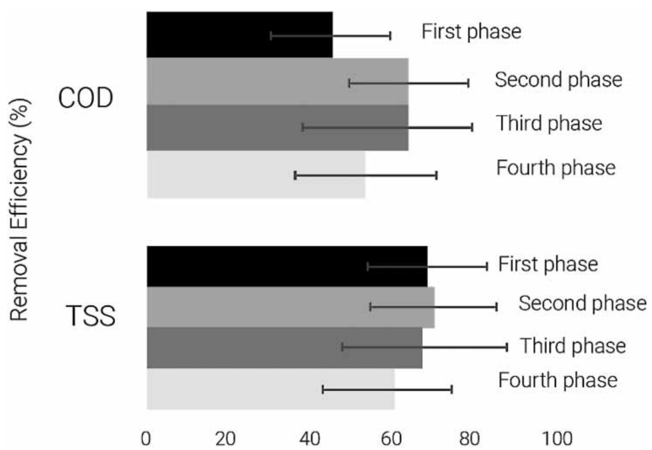

Figure 4 | Mean removal efficiencies of COD and TSS during the four experimental phases.

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Decezaro *et al.* (2019) reported a negative correlation between COD removal efficiencies and HLR which was consistent with our experiment during the first and second phases (Figure 3(a)). By applying lower HLR values, the wetland had the opportunity to reaerate, inducing aerobic degradation of the microorganisms with the longer contact time, which increased the COD removal. Paing *et al.* (2015) also found that COD removal was relatively constant for HLR up to 0.6 m d^{-1}, and gradually decreased and displayed higher variability for higher HLRs.

On the other hand, although the principal removal mechanism of TSS is filtration, we found no correlation between TSS removal and HLRs (Figure 3). This finding is in line with Millot *et al.* (2016) which found that HLRs had no significant influence on TSS removal in the FS-FVFCWs when HLR increased from 0.36 to 0.64 m d^{-1}. Our findings showed that increasing the HLR to values up to 0.94 m d^{-1} had a limited impact on the TSS removal efficiencies. Similarly to COD removal, the decrease in TSS removal during the third and fourth phases seems to be due to the reduction in resting time.

3.3.2. Organic loading rate

The COD and TSS loads varied depending on the HLRs applied to each experimental phase and the raw wastewater concentrations. The mean values of COD and TSS loads were 172 g COD m^{-2} d^{-1} and 150 g SS m^{-2} d^{-1} for the HLR of 0.94 m d^{-1} which represented 57 and 100% of the nominal loads and 109 g COD m^{-2} d^{-1} and 77 g SS m^{-2} d^{-1} for the HLR of 0.56 m d^{-1}. which represented 36 and 50% of the nominal loads. As can be seen, the COD loads consistently remain below the nominal load, whereas the average TSS load at the highest HLR equals the nominal load. This observation provides further insight into the clogging effect discussed in the previous section, whereby the pilots experienced a higher solids load during the third phase (0.94 m d^{-1}) compared to the other phases. Still, the organic and solids loads never exceeded the nominal load. Under these conditions, the treated and applied loads of COD and TSS are shown in Figure 5.

We observed a significant correlation between the COD removal efficiency and the OLR applied only when the feeding and resting periods were 7 days each (p-value = 0.018). In contrast, in the alternative operational strategy with 3 days of feeding and 6 days of resting, we found a significative correlation between TSS removal and its loading rate (p-value < 0.01) (Figure 3). These results may be affected by three particularly high concentrations during the 3 days of feeding and 6 days of resting strategy which represented loads over 500 g m^{-2} d^{-1} (Figure 5).

Previous studies have shown mixed results regarding the relationship between effluent quality and OLRs. For example, Ruiz-Ocamp *et al.* (2022) reported higher outlet concentrations when loading rates were increased from 195 to 300 g COD m^{-2} d^{-1} using FS-FVFCW, whereas Paing *et al.* (2015) observed that there was a marginal correlation between effluent quality and OLRs within the range of 40–50 g BOD_5 m^{-2} d^{-1}. Our results indicated that the increase of OLRs also increases the removal efficiency of the contaminants analysed (COD and TSS) at least for one operational strategy.

We also found that high HLRs up to 0.94 m d^{-1} can be applied to FVFCWs without compromising removal efficiency, as long as adequate limits are established to avoid overloading the treatment units, although, prolonged exposure to high organic overloads could damage microbial activity and decrease the system performance (Molle *et al.* 2006).

3.3.3. Air temperature

Air temperature showed no significant influence on COD and TSS removal (p-value = 0.74, p-value = 0.28, respectively, Figure 3). In Northern Tropical Andes, the temperature variation during the study period was only 9 °C between the maximum and minimum average temperature, which is lower than most cases of VFCWs in Europe (Stefanakis & Tsihrintzis 2012; Ruiz-Ocamp *et al.* 2022). Furthermore, the average temperature in Northern Tropical Andes is relatively low compared to the tropical climate recommended for the French system design. This can affect the performance of the pilots; thus, the obtained results were expected for these climatic conditions.

3.3.4. Precipitation

According to our findings, precipitation only influenced COD removal and not TSS removal (Figure 3). Precipitation during the period that each wetland was resting before the next feeding batch (PRECresting) for the two operational strategies, showed a negative correlation with COD removal with p-value = 0.039. However, precipitation 1 day before the sample was taken (PREC1day) showed a negative correlation with COD removal only for the 3 days of feeding 6 days of resting strategy, and precipitation during the hour of the sampling batch (precipitation batch) did not show any significant influence on COD and TSS removal (p-value = 0.24, p-value = 0.69, respectively). The negative correlations suggest that the rainfall which was infiltrated during the resting period may have washed some bacteria from the filter media and reduced the removal efficiency. However, the precipitation during the feeding period did not seem to affect the performance of the system.

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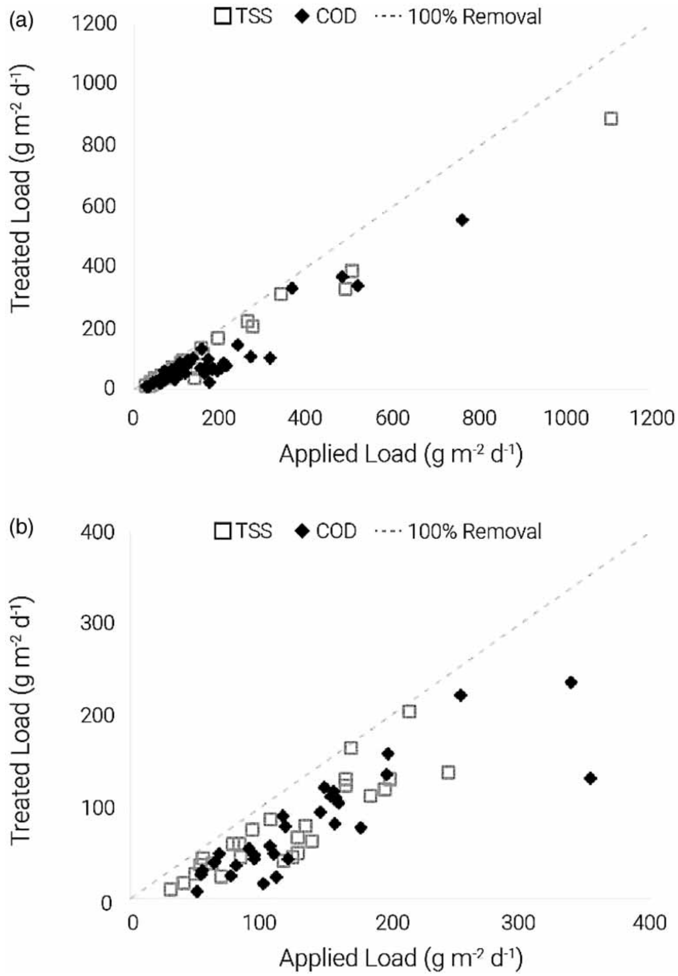

Figure 5 | Treated and applied loads of COD and TSS, and 100% removal (a) for 3 days of feeding and 6 days of resting and (b) for 7 days of feeding and 7 days of resting.

3.4. Land requirement

By increasing the HLR without compromising the effluent quality, the land requirement of the FVFCW can be reduced substantially, leading to lower investment costs which is a major challenge for wastewater treatment in many countries. Specifically, when the HLR is increased from 0.37 to 0.56 m d^{-1}, the surface area requirement for an FS-FVFCW can be reduced by 33% m^2 Pe^{-1} bed^{-1}. Further, the area requirement can be reduced by 60% m^2 Pe^{-1} bed^{-1} in case of 0.94 m d^{-1} HLR, but maintaining the operational strategy when the resting period is the double of the feeding period. The percentages presented here correspond to conditions when the wastewater comes from a combined sewer system, which should be considered for any comparison. The reductions in the surface area of treatment represent a significant economic aspect when choosing this type of wetlands for treating raw wastewater. Additionally, the total area of treatment can be further reduced as no primary treatment is required.

3.5. Comparison with other systems

Previous studies show that most FVFCWs are usually loaded with HLR close to or below the classic design value of 0.37 m d^{-1}. In France, Morvannou *et al.* (2015) identified 380 plants with the two-stage Vertical Flow Constructed Wetlands (VFCWs) that operated with a mean hydraulic load of 0.37 m d^{-1}, Paing *et al.* (2015) analysed 169 operating systems, including classical VFCWs and compact VFCWs, which the majority were loaded with HLRs lesser than 0.4 m d^{-1}, with a few exceptions of HLRs higher than 0.6 m d^{-1}. Silveira *et al.* (2021) analysed four classical VFCWs that had average HLRs ranging from 0.21 to 0.46 m d^{-1}. In Brazil, studies on FS-VFCWs located in Belo Horizonte reported and applied an HLR of

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Table 2 | Hydraulic limits for diluted influent (R: resting period, F: feeding period)

	Molle *et al.* (2006)				Present study	
Deposit layer	0–10 cm		10–25 cm		In development (0–3 cm)	
Hydraulic overload	Once a week	Once a month	Once a week	Once a month	Continuous	
Operational strategy	R = 2 × F		R = 2 × F		R = 2 × F	R = F
m day^{-1}	1.8	3.5	0.9	1.8	0.94	0.56
m h^{-1}	0.25		0.11		0.93	

around 0.45 m d^{-1} (García Zumalacarregui & Von Sperling 2018; Trein *et al.* 2020). In India, Yadav *et al.* (2018) experimented on a pilot-scale two-stage VFCW applying two HLRs: 0.15 and 0.225 m d^{-1}. Few studies have experimented with applying higher HLRs to the units due to infiltration and rainwater that enters combined sewers. In the UK, Pereira Gómez (2016) investigated the two stages of FVFCWs with HLRs from 0.52 m d^{-1} for the dry weather flow up to a maximum of six times during storm events. Molle *et al.* (2006) demonstrated that the French system can accept punctual HLRs of up to 4 m d^{-1}, and continuous HLRs over five months of 1.8 m d^{-1}, establishing hydraulic limits for diluted influent based on infiltration rate, height of the deposit layer and oxygenation of the filter. The hydraulic limits proposed by Molle *et al.* (2006) and those obtained in this study are presented in Table 2.

4. CONCLUSIONS

The modified First Stage of the FVFCWs can be applied in Tropical Andes with good results, making this technology suitable in places with similar climatic conditions and that treat wastewater with high dilutions overcoming the sludge problem from primary treatment. The results indicated that it is possible to use higher HLRs (up to 0.94 m d^{-1}) in this type of wetlands but maintain the design recommendations for temperate climate, i.e., resting the treatment units for the double of time to improve removal efficiencies. However, the system can cope with HLRs in the range of 0.56 m d^{-1} if the resting period is reduced. Mean removal efficiencies of COD and TSS of 64 and 70%, respectively, were obtained when the HLR was 0.56 m d^{-1} with 3 days of feeding and 6 days of resting. Furthermore, our findings suggest that increasing the HLR to values up to 0.94 m d^{-1} had a limited impact on TSS removal efficiencies. Concerning the OLR, the removal efficiencies of TSS were either increased or not correlated with increasing OLRs for specific feeding/resting strategies. This suggests that high OLR can be applied to FVFCWs without compromising system efficiency.

Finally, applying higher HLRs to the filters led to a significant reduction in land requirements, with reductions of around 30 and 60% without compromising the effluent quality.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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