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Septage treatment using the First Stage of French Vertical Flow Constructed Wetlands: From the beginning to the closure of the system

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ABSTRACT

The First Stage of French Vertical Flow Constructed Wetlands (FS-FVFCW) offers a sustainable solution for treating septage. The system operates through distinct phases: start-up, full operation and final rest. During full operation, factors such as feeding duration, rest periods and percolate impounding significantly affect performance. This study assessed the performance of a pilot-scale Modified FS-FVFCW in Northern Tropical Andes, from start-up to closure stages under three operational scenarios. These scenarios varied in planted/unplanted conditions and percolate drainage/impounding. A four-month start-up phase proved adequate for vegetation growth and adaptation, achieving over 50% COD removal efficiency. Percolate retention (impounding) during operation notably improved COD and TS removal, increasing efficiencies from 49% to approximately 90% for COD and from 39% to around 70% for TS. Plant presence contributed to mosquito control and odour reduction but had minimal impact on removal efficiencies. The pilot demonstrated significant dewatering potential, with sludge deposit samples showing water content below 76% across all scenarios after 24 h; and a 10% reduction in VS/TS ratio during the operational resting period. After a 5-month closure, the sludge deposit layer exhibited organic matter content similar to long-rested sludge, albeit with persistent faecal contamination.

1. Introduction

In developing countries, including Ecuador, a significant portion of urban population (15%) depend on on-site technologies like septic tanks for wastewater treatment due to the absence of sewage collection systems (Sturzenegger et al., 2020). The US Environmental Protection Agency (2024) recommends desludging septic tanks every three to five years or when biosolids exceed 30% of their volume for their correct operation. Sludge from basic on-site sanitation systems, including septic tanks, is known as faecal sludge and septage (FSS) (Shukla et al., 2023). Septage comprises a mixture of sludge and black water with substantial pollutants and water contents (Saeed et al., 2023). While 78% of FSS generated In Europe and North America is securely managed, in Latin America it is only 34% (UNICEF/WHO, 2021). Without further control, the discharge of untreated septage, is a potential source of unpleasant smell, mosquito breeding and health problems (Shukla et al., 2023).

In accordance with Uggetti et al. (2010) one technological solution for treating sludge, including septage, involves utilizing constructed wetlands, also known as Sludge Treatment Wetlands (STWs) or Sludge Treatment Reed Beds (STRBs). These systems have become increasingly significant as a cost-efficient and technically viable method for the dewatering, stabilization, and mineralization of different sludge types (Karolinczak and Dabrowski, 2017; Nielsen and Stefanakis, 2020). However, the knowledge about sludge quality parameters and how these affect capacity and performance of STWs remains insufficient (Brix, 2017).

STWs have some advantages, such as operation for long periods without requiring sludge removal and low cost of implementation. However, limitations include the need for more studies on the sanitary aspects, standardized size criteria and the elimination of pathogens and micropollutants (Koottatep et al., 2001; Suntti et al., 2011). Drawing from the experience, it is clear that the key to the effective operation of

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STWs lies in their correct design and construction. Nonetheless, uncertainties persist on the system design (Stefanakis et al., 2014) and operation schemes. The system is usually designed based on sludge quality characteristics and on the local climatic conditions (Nielsen and Willoughby, 2005). According to Brix (2017) meticulous caution is advised when considering the extrapolation of STWs beyond their established and documented regions of application.

The First Stage of French Vertical Flow Constructed Wetlands (FS-FVFCWs) represents a sustainable alternative for septage treatment. These wetlands are primarily designed for treating raw wastewater with the consequence of a deposit sludge layer formation on the top of the bed, which would resemble the organic deposit or sand layer of STWs. This wetland system allows the sludge layer reduction by dewatering and mineralization over the long term (Kim et al., 2018).

The functioning of the STWs involves various phases during a system life cycle, including commissioning, full operation, emptying and re-establishment (Brix, 2017). In the commissioning phase, it is recommended to apply a solids loading rate (SLR) at a reduced level (10 to 30 $kg.m^{-2}.yr^{-1}$) to facilitate plant growth (Nielsen, 2011). The operational phase includes feeding, operational rest and final rest. According to Gholipour et al. (2022), the average feeding durations are between 2 and 6 days, while the average operational rests are between 7 and 22 days, depending on the climatic conditions, with less days for arid and tropical climate and more days for temperate climate. During this phase, the performance of STWs is influenced by various factors, such as plant types, bed maturity, climate, sludge characteristics, hydraulic loading rate (HLR), SLR, and loading frequency (Bassan et al., 2014). Among these factors, the presence and distribution of plants can significantly contribute to septage treatment, which hence affects the performance of STWs (Gagnon et al., 2013). In particular, plant species impact dewatering performance and by-product quality through root structure, and plant morphology and distribution (Kołecka et al., 2018). Similarly, percolate impounding (retention period) also influences the performance of STW. Koottatep et al. (2005) discovered that percolate impounding significantly improved N removal, while its effects on Total Solids (TS) and Chemical Oxygen Demand (COD) removals were insignificant. Specifically, removal of Total Kjeldahl Nitrogen (TKN) improved from 80% without impounding period to 94% with 12 days of percolate impounding. The effects on TS and COD removals were minor, with TS removal of 78% without and 73% with 12 days of impounding, and COD removal of 95% without and 97% with impounding. In contrast, Manjate (2016) found that percolate impounding enhanced the biodegradation of organic matter, with a COD removal efficiency of 71% without impounding and 85% with seven days impounding.

There is a lack of design guidelines for final resting periods, however the length of that period is depended upon the targeted degree or final dry solids content and their desired application (Brix, 2017). Generally, there is an absence of comprehensive studies covering the entire life cycle of STWs. Therefore, studying the whole cycle, from commissioning to closure, testing the impact of important driving factors on the performance in highlands regions is essential to completely understand and improve the behaviour of the system.

According to Bassan et al. (2014) with the advances achieved, current research has produced promising results and it is expected that STWs will be adopted more extensively around the world, especially in tropical regions of low-income countries. There are few studies of STWs in Latin America, however, there are no reports of STWs in Ecuador or in highlands (Gholipour et al., 2022). This study aims to assess the performance of a pilot-scale Modified FS-FVFCW installed in Northern Tropical Andes, throughout the start-up to the closure stages under three operational scenarios. Objectives include: (1) Exploring the whole cycle: from start-up to closure of the FS-FVFCW treating septage; (2) Testing the effect of vegetation and retention time on the performance of the FS-FVFCW; and (3) assessing the dewaterability and development of the sludge deposit layer when the FS-FVFCW is treating septage.

2. Materials and methods

2.1. Study site

This study was conducted in the pilot-scale Modified FS-FVFCW which is located near the Ucubamba Wastewater Treatment Plant (WWTP) in Cuenca – Ecuador (2°52′15.1″S, 78°56′30.8″W). The elevation of the site is 2500 m.a.s.l. placed at the South Andes of Ecuador. The annual average temperature is 16.3 °C and the average annual rainfall is the 879 mm. The rainy season occurs from mid-February until early July and from late September until mid-November, while the dry season occurs the rest of the year (Buytaert et al., 2006).

The superficial area of the pilot was 9.81 m^2 with a length to width ratio of 1.3 to 1 and a 1 m depth. The substrate consisted of three layers of different size of gravel following the configuration of the FS-FVFCW, recommended by Molle et al. (2005) although with slightly different diameters due to material availability. From top to bottom, the filter media was 30 cm of small gravel (⌀ 2–10 mm); 20 cm of middle gravel (⌀10–20 mm); and 20 cm for the drainage layer (⌀ 20–60 mm). Additionally, two ventilation pipes with a diameter of 110 mm (Fig. 1) were installed at the base of the pilot to oxygenate the root zone, prevent anaerobic conditions, reduce odours and maintain the biological activity.

2.2. Experimental setup

The pilot was studied throughout the start-up to the closure stages under three operational scenarios which were run in sequence (Fig. 2).

The start-up phase, spanning from September 2020 to January 2021, adhered to the recommendations outlined by Bassan et al. (2014) for initiating STWs. This involved irrigating the wetlands with either untreated wastewater or appropriate diluted faecal sludge to promote their establishment. A controlled high load of 0.94 $m.d^{-1}$, comprising 24 daily batches of raw wastewater, was administered during this period. Typically, the initial start-up phase is implemented to facilitate the growth of reeds and enhance their adaptation to the bed environment (Stefanakis et al., 2014). In this study, *Lolium Perenne,* a locally resilient grass species, was selected and planted on the inaugural day of raw wastewater feeding in the pilot system. Feeding persisted for six consecutive days until the vegetation exhibited green appearance and growth. Then, the pilot was rested for 9 days before the next loading. The selection of the feeding and resting intervals was determined by ongoing observation of vegetation development. The primary aim was to acclimate the vegetation to both the prevailing climatic conditions and the loads of raw wastewater.

The operational period started in February 2021 and lasted till April 2022 comprising 32 treatment cycles of feeding and resting phases. During this period, vacuum trucks that empty septic tanks in Cuenca city

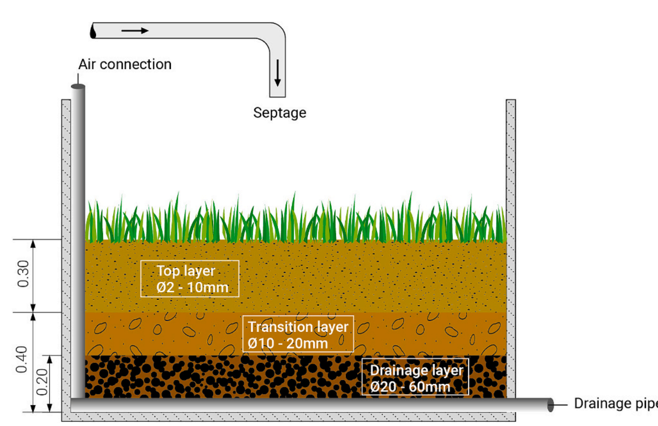

Fig. 1. Diagram of the pilot's configuration.

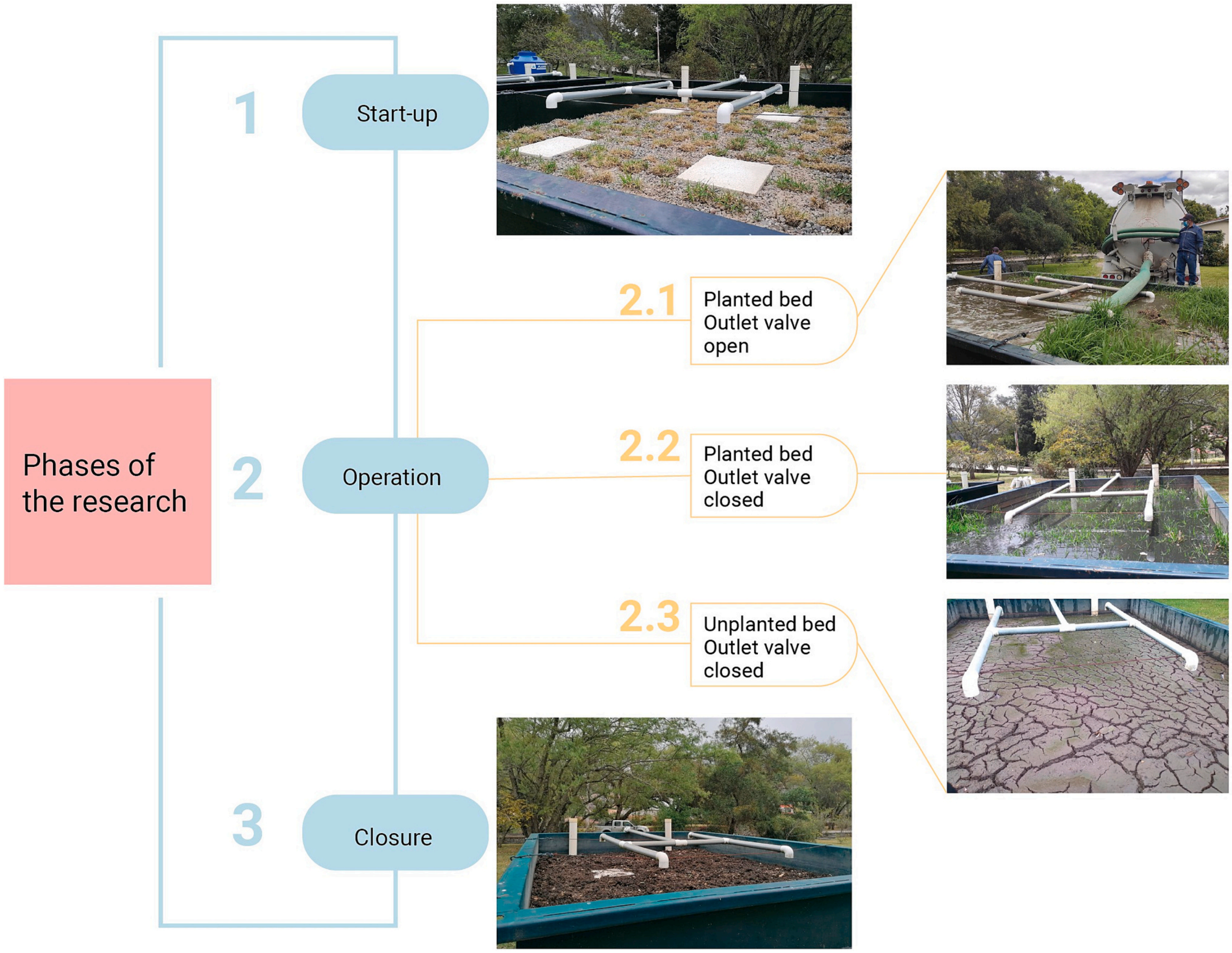

Fig. 2. Scheme with the phases of the research: start-up, operation with three sequential scenarios, and closure.

delivered the septage to the pilot. The aim of this operational phase was to replicate the real-life scenario commonly encountered in Cuenca. This involved the vacuum trucks visiting various septic tanks at different times and without any prior scheduling, and loading the septage directly into the pilot with the hose from the vacuum trucks. One load was considered for one treatment cycle. The volume of one load was variable depending on the amount of septage that the pilot could receive, which fluctuated according to the prevailing operational scenario.

The first operational scenario involved the FS-FVFCW planted and loading septage with the outlet valve open, allowing the drainage of the percolate. The second scenario was set up with the FS-FVFCW planted and the outlet valve closed to retain the percolate. The third scenario was similar to the second, but the FS-FVFCW remained unplanted.

After each loading, the pilot started operational resting for seven to fourteen days. There wasn't strict control over the HLR and SLR due to the variability in septage origin, volume and characteristics.

Following the operational period, the pilot transitioned into its closure stage. Samples of the sludge layer were collected after a cessation period of five months.

2.3. Sample collection and analyses

During the first month of the start-up phase, in situ parameters and physicochemical analyses were performed in samples collected in the influent (raw wastewater) and effluent of the pilot. Dissolved oxygen (DO) and pH were measured four times per day using a WTW Multi3420 probe. Six daily grab samples were taken to analyse Chemical Oxygen Demand (COD) during the 9 am batch.

During the operational phase, samples were obtained from septage at the hose of the vacuum truck during the feeding in every treatment cycle (influent). Additionally, composite samples were collected from the percolate of the wetland outlet (effluent) according to the outlet flow. For the first scenario, samples were taken on the same day as feeding, while for the second and third scenarios, samples were collected after a 7-day interval, immediately following the opening of the outlet valve. All samples during the three scenarios were analysed for COD, BOD_5, Total Solids (TS) and Volatile Solids (VS). Subsequently, samples were collected from the sludge deposit layer at different time intervals during the operational resting: 1 day, 7 days and 14 days after the septage feeding. The objective was to examine the variations in water content within the sludge deposit layer over the course of the days for the three operational scenarios. Ultimately, the Total Solids (TS) and Volatile Solids (VS) content of the sludge deposit layer were analysed when the outlet valve was closed encompassing the second and third scenarios. This analysis occurred both one day and seven days following the loading of the septage.

During the closure stage, six samples were analysed after a 5-month period of final resting. These samples were obtained from two specific locations within the sludge deposit layer, at three different heights (surface, middle and bottom) subsequently mixed. The analysis focused on determining the concentrations of organic matter (OM), carbon, nitrogen, phosphorous and Total Coliforms present in the samples.

COD, TSS, TS and VS in septage samples, were analysed following the *Standard Methods for the Examination of Water and Wastewater*

(APHA/AWWA/WEF, 2012). BOD_5 was analysed using a respirometric system Lovibond BD600. The organic matter, nutrients and indicators of faecal contamination in sludge deposit samples were analysed according to *Laboratory Methods of soil analysis Canada-Manitoba soil survey*.

2.4. Statistical analysis

The experimental results underwent statistical analysis using R software (Version 2023.03.0 + 386). Initially, the data were tested for normality. However, as they exhibited non-normal distribution and independence (time series data), non-parametric tests were subsequently employed. For comparing the three operational scenarios, the Kruskal – Wallis test followed by Bonferroni-Dunn test was applied. In case of the comparison between two scenarios, the Mann-Whitney *U* test was used. A significance level of 0.05 was chosen for *p*-values.

3. Results and discussion

3.1. Start-up period

During the start-up phase, the vegetation exhibited robust adaptation to the bed environment and the high loads of raw wastewater applied, demonstrating normal growth and adhering to the criteria necessary for a successful start-up, as outlined by Stefanakis et al. (2014). The vegetation endured prolonged periods of rest, a crucial factor, especially considering that in the subsequent operational phase, the vegetation would be required to withstand a minimum resting period of 7 days to ensure effective septage treatment.

In situ parameters measured during this period, along with COD concentrations in both influent and effluent of the pilot, are illustrated in Fig. 3. DO concentrations exhibited an increase from influent to effluent, with a mean concentration in the effluent of 4.24 mg/L. This observation indicates the aerobic conditions prevailing in the wetland, indicating successful functioning of the air connection pipes and alignment with the desired aerobic condition. pH shows no significant variation from influent to effluent, with values hovering around 7 to 9.5. This suggest that the biological treatment in the pilot can occur without encountering extreme pH values. The reduction of COD levels commenced in the start-up phase, from an average of 147.50 $mg.L^{-1}$ in the influent to an average of 65.50 $mg.L^{-1}$ in the effluent. However, this reduction has begun at a lower level than projected for the operation phase.

Different recommendations exist regarding the optimal duration of the start-up period. The goal is that the acclimatization period is sufficiently lengthy for the establishment of plant growth and facilitating adaptation to challenging faecal sludge conditions (Andriessen et al., 2019). Stefanakis et al. (2014) recommends the start-up period to last up to 2 years, with shorter periods for warmer climates. However, Andriessen et al. (2019) recommends that the acclimatization phase should take, on average, six months. In this case, the commissioning period was shorter (4 months) although the local temperature could be lower than the optimal temperature for the growth of the plant. The objective was to accelerate the start-up process, enabling units, at any location to swiftly become operational. This duration proved adequate for vegetation growth and adaptation, demonstrating a removal efficiency over 50% for COD.

3.2. Operational period

3.2.1. Raw septage, effluent characteristics and FS-FVFCW general performance

The raw septage exhibited a considerable range of variation during the operational period, as illustrated in Fig. 4, with numerous outliers observed. Septage variability can be attributed to its different sources, including septic tanks with different usage patterns, retention times, emptying practices, treatment performances, construction qualities and groundwater characteristics (Jain et al., 2022). The observed variability agrees with the common variations in faecal sludge characteristics (Andriessen et al., 2019), but is slightly more concentrated than some septage reported in the literature (Gan et al., 2018; Jain et al., 2022). The abundance of outliers suggests that septage arriving at treatment facilities may manifest exceptionally elevated concentrations under real-world conditions, deviating significantly from typical levels. Nevertheless, the effluent variability, as evidenced in Fig. 3, exhibited a notable reduction, contrasting with the peaks observed in influent concentrations. This observation highlights the resilience and efficacy of the FS-FVFCW in managing operational conditions representative of real-world scenarios, consistent with the findings of Sonko et al. (2014).

The mean COD/BOD ratio found in the influent septage was 4.1 with a standard deviation (SD) of 2.0. Septage tends to have a higher COD/BOD ratio compared to domestic wastewater (Jácome et al., 2016). In this case, the ratio suggests the presence of a significant amount of slowly biodegradable organic materials in the influent. Further, the VS/TS ratio found was 0.6 (SD: 0.2) which provides insight into the organic content of the septage.

Mean removal efficiencies during the operation period were 72.1% (SD: 25.3%) for COD, 73.6% (SD: 23.5%) for BOD5, 57.3% (SD: 29.5%) for TS and 63.18% (SD: 27.9%) for VS. These values are satisfactory, since the pilot was a new operating system. However, it is noteworthy that both COD and TS removal rates were lower than typical STWs efficiencies, which generally fall between 85% to 99% for COD and 64% to 96% for TS, as documented in previous studies (Karolinczak and Dabrowski, 2017; Kengne et al., 2011; Kim et al., 2018; Sonko et al., 2014). The primary difference behind may be due to the media configuration of the STWs. Previous studies had a top layer of sand, whereas our FS-

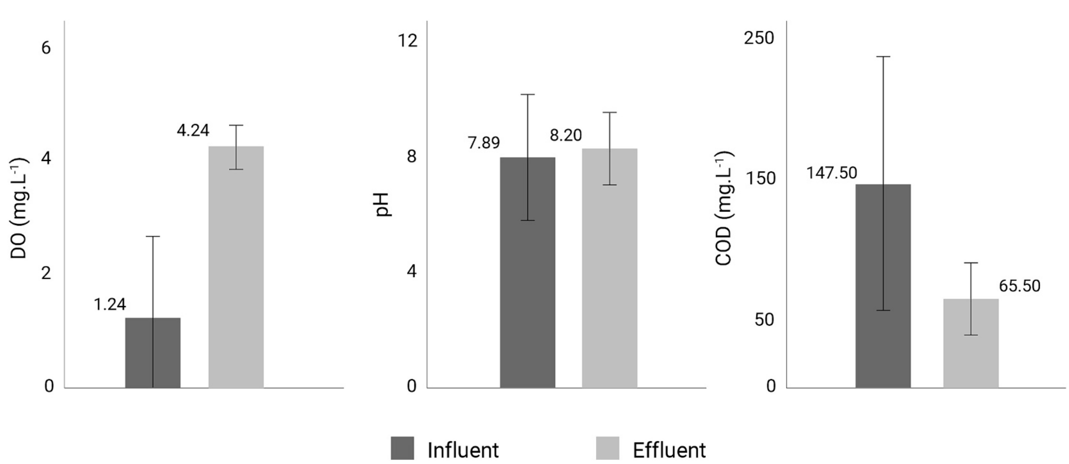

Fig. 3. DO, pH and COD mean values in the influent and effluent of the pilot during the start-up period.

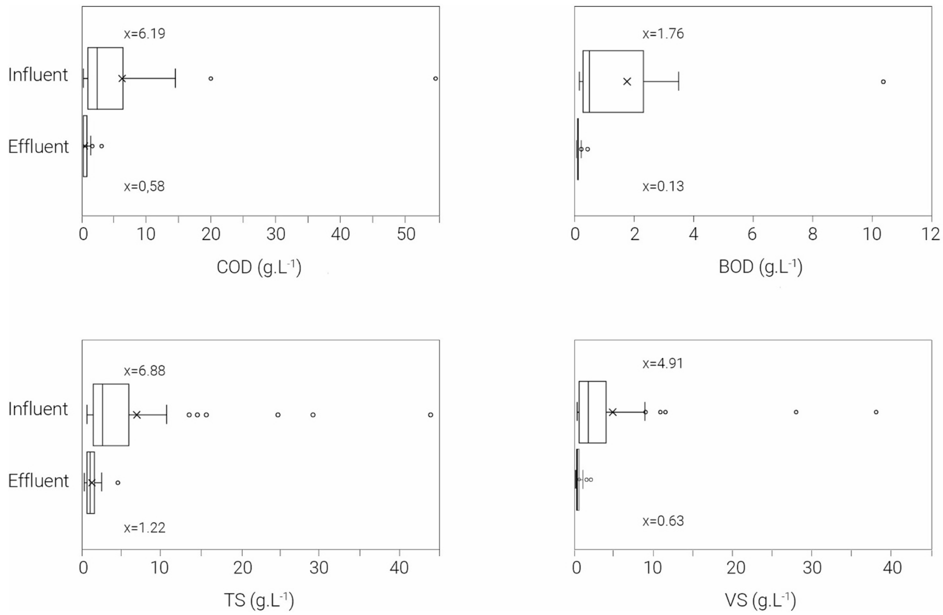

Fig. 4. Influent and effluent concentrations of COD, BOD, TS and VS during the operational period (x = mean value).

VFCW had a top layer of gravel with particle sizes ranging from 2 to 10 mm. In the FS-VFCW system, the treatment performance is enhanced by the sludge deposit layer that forms over time during operation (Molle, 2014). Since this layer was still developing during the study period, it may have influenced the pilot system's performance. Additionally, we used *Lolium Perenne* instead of the various reed species used in other studies. This variation in vegetation could also have contributed to the observed differences in treatment efficiency. Furthermore, the efficiency values obtained at pilot-scale are usually lower than those occurring in large scale because of less shortcuts (Vincent et al., 2011).

3.2.2. COD and TS removal under three scenarios

Table 1 displays the percentages of COD and TS removals, along with the HLRs and SLRs for each of the three scenarios studied. The application of HLRs and SLRs was regulated based on the pilot's volume capacity.

The pilot system was more effective at handling incoming septage in an unsaturated condition as seen with the higher HLR observed in scenario 1. The free flow of percolate allowed for processing a larger volume of septage without flooding. In contrast, retained percolate in scenarios 2 and 3 constrained septage volume to avoid flooding, which resulted in lower HLRs. Nonetheless, HLR values also varied significantly between scenarios 2 and 3. COD and TS removals dropped from 90.8% and 76.6% in scenario 2 to 88.1% and 60.9% in scenario 3, respectively, despite both scenarios operated with the outlet valve closed. This discrepancy suggests a potential clogging issue within the pilot system, consistent with Molle (2014) who indicates that decreasing flow rates imply an increased clogging risk in wetlands with high solids content. Additionally, the HLRs applied in this study are comparatively lower than those employed in other investigations (ranging from 0.05 m.d-1 to 0.11 m.d-1) (Bui et al., 2018; Karolinczak and Dabrowski, 2017). Despite the application of lower HLRs, the pilot may have experimented clogging issues in the last operational stage, prompting further investigation into potential causal factors beyond the outlet valve closed.

SLRs were influenced by both the HLR and the variable influent solids concentration, leading to the values presented in Table 1. These SLR values are similar to the mean values (50–70 kg.m^{-2}.y^{-1}) reported for temperate climates, but lower than the mean value (101 kg.m^{-2}.y^{-1}) for tropical climates (Brix, 2017; Gholipour et al., 2022). Temperature emerges as the key factor influencing the design considerations of STWs. The local temperature regime resembles that of temperate climates, but without distinct seasonal variations typically associated with summer and winter.

The pilot showed a notably higher COD and TSS removal when the percolate had a retention period of 7 days compared to no retention period. During the first scenario, the removal efficiencies showed notable fluctuations, as evidence by a high standard deviation. Moreover, the SLRs exhibited higher values along with wide fluctuation. These observations indicate that high SLRs may have impacted the stability of the pilot, potentially hindering its performance.

3.2.3. Influence of retention period (percolate impounding)

To test the impact of percolate impounding, the Kruskal-Wallis test followed by Bonferroni-Dunn test was conducted to compare the three operational scenarios. The results obtained are shown in Table 2. Scenario 1 represents the unsaturated condition, whereas scenarios 2 and 3 represent seven days of retention period with percolate impounding.

Upon analysing the results presented in Table 2, it is evident that the retention time, characterized by the contact time between septage and filtration material, positively influenced the performance of the pilot in

Table 1
Operation and performance conditions during the three scenarios.

Scenario	Retention time	Parameters							
		COD removal (%)		TS removal (%)		HLR (m.d^{-1})		SLR (TS kg.m^{-2} y^{-1})	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	None	49.6	21	39.1	28.6	0.037	0.012	65.9	137.52
2	7 days	90.8	9.6	76.6	13	0.016	0.006	35	30.2
3	7 days	88.1	9.9	60.9	31.6	0.008	0.004	16	23.5

Table 2
Exact p values of the Kruskal-Wallis test followed by Bonferroni-Dunn test for comparison of the three operational scenarios. *: $p \leq 0.05$, **: $p \leq 0.01$, ***: $p \leq 0.001$.

Scenario	Variables			
	COD removal (%)	TS removal (%)	HLR (m d^{-1})	SLR (TS kg m^{-2} y^{-1})
1–2	< 0.001***	0.013*	0.031*	0.71
1–3	0.003**	0.32	< 0.001***	0.043*
2–3	0.61	0.74	0.19	0.11

terms of COD removal (significant difference between scenario 1 and the other two scenarios for COD removal). On the contrary, for TS removal, the influence of retention time is less apparent, as there is only a significant difference between the first and second scenarios. In this context, it is plausible that the inadequate development of the sludge deposit layer in the first scenario could have affected the removal of TS.

The influence of percolate impounding on COD removal is consistent with the research findings of Manjate (2016), who noted that percolate retention enhances the biodegradation of OM. However, this observation contrasts with the outcomes of Koottatep et al. (2005) who reported that the retention period of percolate inside the bed exhibited significant impact on N removal, while its effects on TS and COD removals were insignificant.

Conversely, in analysing TS removal and considering the results of Koottatep et al. (2005) who found that the filtering capacity of STW remained unaffected when a specific retention time was established, and since we did not find a consistent difference (as observed in COD) between scenario 1 and the other two, it can be suggested that the formation of the sludge layer is the primary factor affecting performance in scenario 1 for TS removal. This proposition is further supported by the findings of Molle (2014) which suggest that the formation of a sludge layer is known to enhance filtration.

The plants were adapted to septage and exhibited normal growth in both no saturated conditions (left on Fig. 5) and with percolate retention (right on Fig. 5). Despite variations in HLRs and SLRs the vegetation developed always well. To maintain the unit effectiveness, the plants were harvested regularly every 3 to 4 weeks.

3.2.4. Influence of plant growth

Macrophytes play a crucial role in wetlands (Bassan et al., 2014) and often contribute to the removal of macro and micro pollutants through uptake pathways (Jain et al., 2022). However, it is mentioned that for OM decomposition, plant contribution is not as important compared to microorganism activity (Stefanakis et al., 2014). The results obtained showed that plants applied here (*Lolium perenne)* did not significantly affect the TS removal, as there are not significant differences between scenarios 1–2 (planted) with scenario 3 (unplanted) (Table 2). Although there was a significant difference in COD removal between scenario 1 and 3, no difference was observed between scenario 2 and 3 (Table 2). The difference observed for COD removal between scenario 1 and 3 can be attributed to the analysis conducted on the influence of the sludge deposit layer and percolate impounding, as discussed earlier. Nevertheless, it is important to acknowledge the positive impact that the vegetation may have when enhancing COD removal efficiency. Moreover, it is noteworthy to highlight the contribution of plants beyond their efficiency in removal processes. The presence of plants mitigated mosquito breeding and dissipated odours emissions within a few hours following each septage loading. In contrast, the unplanted condition exhibited a prolonged persistence of odours and mosquito presence until the following day.

Furthermore, we found that plants had no effect on the reduction of HLR in scenario 3 compared to 2 (Table 1) as there was no significant difference between 2 and 3 for HLR or SLR (Table 2). The capacity of the pilot to accept a certain volume could have decreased because of the percolate impounding or as a part of the system clogging. This shows that the resting time after each loading may have been insufficient for the wetland to recover.

3.2.5. Sludge deposit layer

3.2.5.1. Sludge dewatering. One of the main purposes of septage treatment is to dewater and stabilize the sludge. After septage loading onto the wetland, the majority of the water percolated through the filter, and the solid fraction stayed on the surface of the bed. Fig. 6 shows the water content of the sludge deposit layer after 24 h, 7 and 14 days during the operational resting period before the next loading for the three scenarios. Water content consistently decrease across the samples over the course of the days (from day 1 to day 7 and day 14) in all three scenarios.

After 24 h, most of the sludge deposit samples presented water content below 76% with some samples having even 60% water content, in the three scenarios. This finding shows the great dewaterability potential of the wetland that needs only 1 day to dewater the sludge to acceptable values (≤70%) for landfill disposal in Ecuador (TULSMA, 2015). During the next days, most values ranged between 40% to 80%, with a few samples below 40% water content.

The plants play a role in promoting the dewatering process in faecal sludge (Andriessen et al., 2019), but here there was not any influence of the scenarios (with and without vegetation) over the dewaterability of the sludge deposit layer within the first 24 h (*pvalue* = 0.3024). The values obtained were not dependent on the presence of the vegetation. It must be said here, that the vegetation used in this study was completely

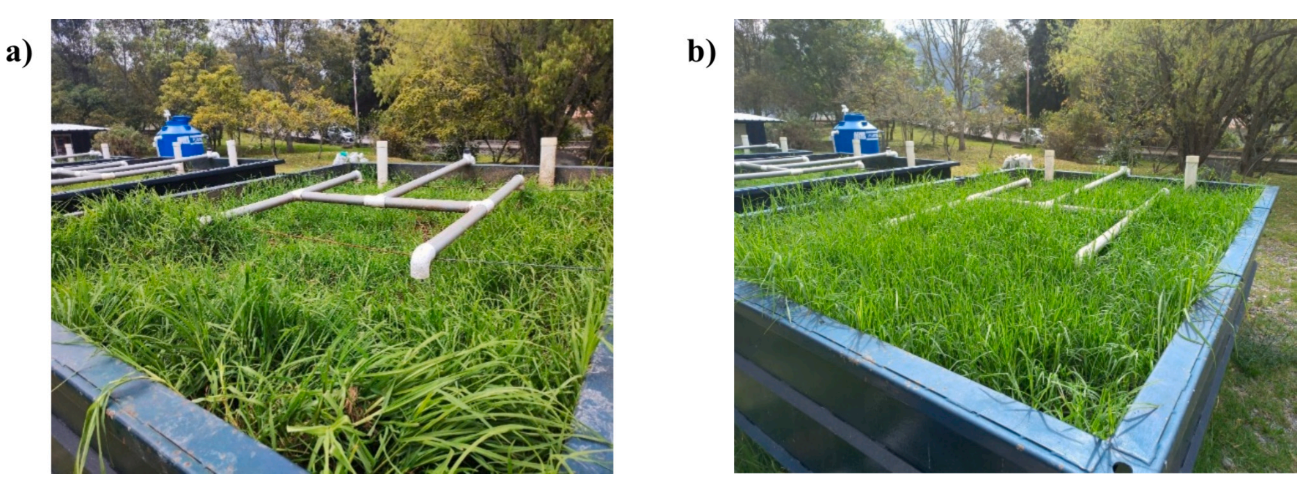

Fig. 5. Growth of vegetation in a) unsaturated conditions and b) with percolate retention in the septage treatment pilot.

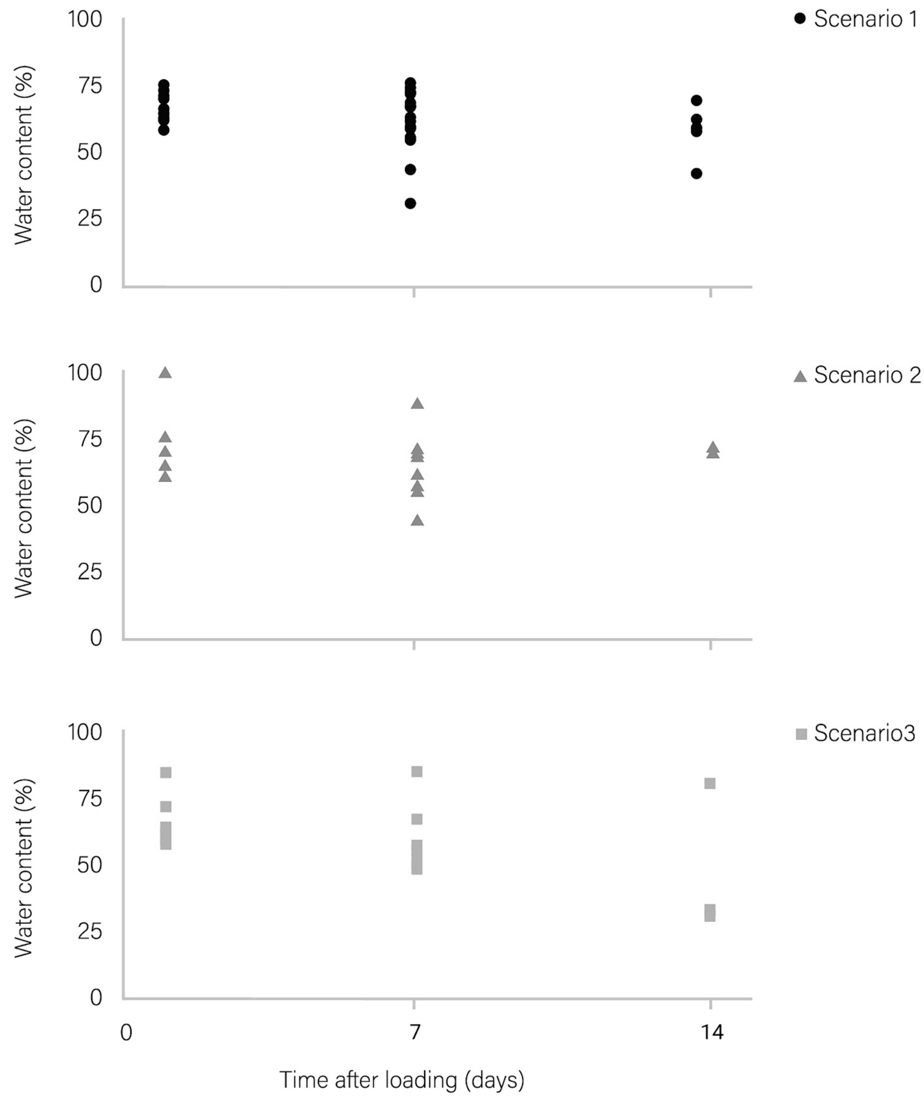

Fig. 6. Water content percentage on sludge deposit samples in the three operational scenarios.

different from the vegetation that Andriessen et al. (2019) mentions which should pose the difference.

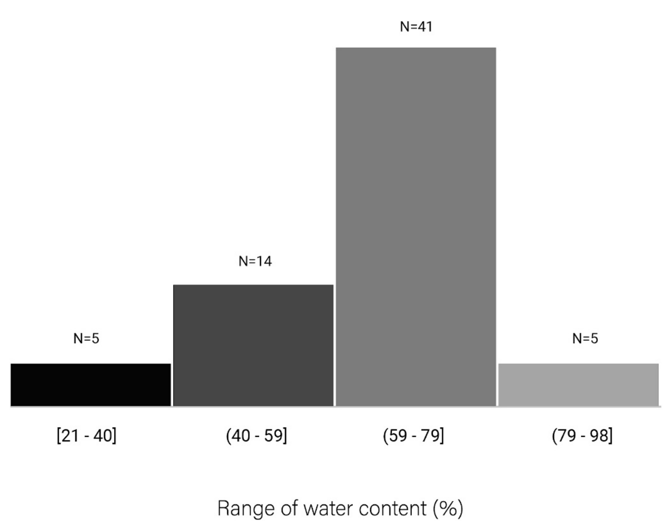

Fig. 7. Categories of sludge deposit samples according to their water content (N = number of samples in each range).

Fig. 7 displays the water content of the sludge deposit layer samples classified into four distinct categories. The majority of the data falls within the 60 to 80% range, while the remaining data points are distributed across categories representing lower water content, with only a few samples exceeding 80%. According to Brix (2017), with traditional methods the sludge generally achieves a dry matter content of approximately of 20%, while in STRBs the sludge can attain a dry matter content ranging from 20% to 30% and under optimal circumstances, up to 40%. Considering this, the wetland appeared to be operating effectively for achieving the results showed here. Notably, only one sample exhibited a water content exceeding 90%, suggesting an unusual circumstance or anomaly.

3.2.5.2. VS/TS ratio. The ratio of VS to TS is one of the key criteria that indicates the amount of decomposable sludge (Brix, 2017). This ratio was plotted for both the initial day and 7 days following septage loading (Fig. 8) to assess the reduction achieved within that timeframe. VS/TS ratios were in the range of 40% to 85% with a mean of 64.8% (S·D: 11.5%). Those values align with the ones obtained by other studies in temperate climates (53–55%) and tropical climates (42%) (Gholipour et al., 2022).

There was a slight reduction in the VS/TS from day 1 to day 7 in 14 of the 18 loading periods analysed. The reduction was in the range of about

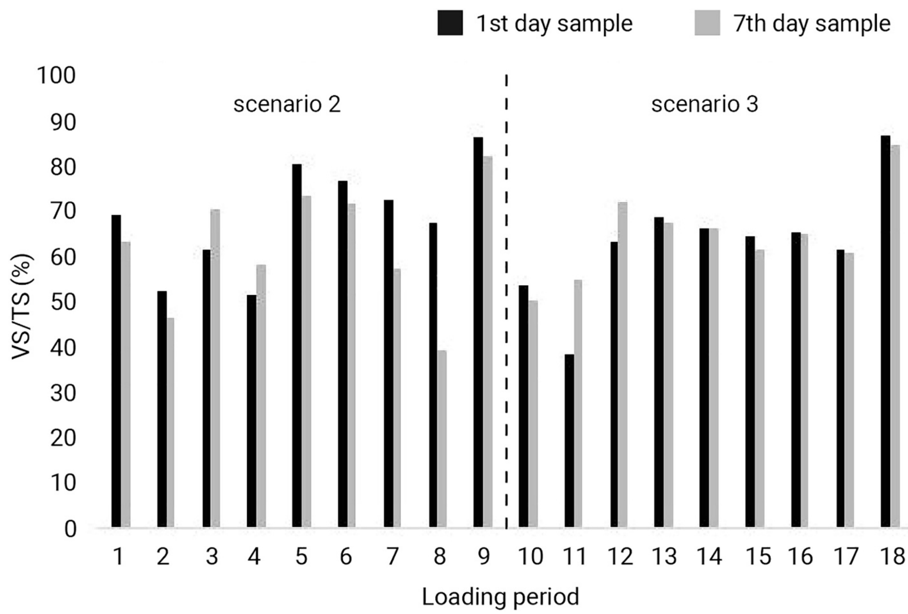

Fig. 8. VS/TS relation in the sludge deposit samples taken after 1 day, and 7 days of loading.

10%. However, according to Wang et al. (2021) the VS reduction rate of sludge in the STW was 25–30% which was in turn much lower than that of aerobic digestion (40–55%) and anaerobic digestion (35–50%). Thus, higher VS reduction was not satisfactorily achieved in this research.

Furthermore, there was not enough evidence to conclude that there was a significant difference between the reduction of the ratio VS/TS when the pilot was planted and unplanted ($pvalue = 0.091$). However, it might be noticed that the events when the ratio VS/TS increased from day 1 to day 7 were on both scenarios. It is assumed that in the case of events involving an increase in the VS/TS ratio in the scenario with plants, it may be due to pruning's that left remnants of organic solids on the pilot surface, contributing to volatile solids. Meanwhile, in the case of events in the wetland without plants, the unusual increase in VS may be attributed to some transport of vegetation from the surrounding area to the pilot, possibly due to wind. Nonetheless, the low organic reduction rate of this technology for septage treatment is a disadvantage that can hinder its acceptance for this purpose (Wang et al., 2021).

3.3. Wetland system closure

Previous studies have not established specific design guidelines concerning the duration of the final resting period. However, the length of this phase can vary depending on the intended application of the final dried solids (Brix, 2017). In this study, the characteristics of the sludge layer were assessed after a 5-month final resting period (after 15 months of operational period), with the findings presented in Table 3. Trein et al. (2020) found that the OM content of a sludge deposit layer in a French VFCW treating raw wastewater ranged around 50% after 10 years of accumulation and approximately 60% with less than three years of accumulation. Instead Dotro et al. (2017), suggests that the deposit layer typically contains around 40% OM, due to gradual mineralization over several years. Here a figure of 31.55% (S·D. 13.71%) was recorded after a short period of accumulation, and final resting. Dotro et al. (2017) also suggests that this sludge can serve as a source of OM and phosphorous for field application, subject to local regulations. Here phosphorous accounts for 10.02% (S.D: 5.50), falling withing the low range (<12%) for soil fertility as per Villasanti et al. (2013). Conversely, nitrogen levels indicate soil fertility (>0.3%).

In terms of biological characteristics, Andreoli et al. (2007) mentions that natural drying can substantially reduce pathogenic organisms through exposure to sunlight. However, Total Coliforms concentrations after the 5-month period suggest that the sludge layer remains unsuitable for application on land considering the US Environmental Protection Agency (2024) regulation.

Table 3
Composition of the sludge deposit layer.

Measured parameters	Sludge deposit layer	
	Mean	SD
Organic Matter (%)	31.55	13.71
Nitrogen (%)	1.94	0.90
Carbon (%)	16.71	7.27
Phosphorous (%)	10.02	5.50
Total Coliforms (CFU/g)	3000	–

4. Conclusions

The FS-FVFCW is effective in septage treatment, achieving satisfactory removal efficiencies for COD, BOD_5, TS and VS during its operational period. The retention period of percolate (percolate impounding) significantly impacts COD and TS removal, indicating the importance of considering this factor in the system design. Plant presence contributes to mosquito control and odour reduction but minimal impacts removal efficiencies.

The sludge dewaterability potential of the FS-FVFCW within 24 h, was excellent, with a subsequent 14-day resting period further reducing water content. However, the low organic reduction rate (VS/TS ratio) found in the sludge deposit layer is a disadvantage of this technology.

The analysis of the sludge deposit layer composition in the closure stage revealed an OM content similar to that of sludge that has been resting for several years, alongside the continued presence of faecal contamination after a 5-month period of final resting.

This study provides valuable insights into the challenges and potential solutions for septage treatment in developing countries, showcasing the promising performance of the FS-FVFCW pilot.

CRediT authorship contribution statement

María B. Arévalo-Durazno: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jorge A. García**

Zumalacarregui: Writing – review & editing, Supervision. **Long Ho:** Writing – review & editing, Investigation. **Andrea Narváez:** Data curation. **Andrés Alvarado:** Writing – review & editing, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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