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Research Paper

Raw sewage treatment by a single-stage vertical flow constructed wetland: a case study in Brazil

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ABSTRACT

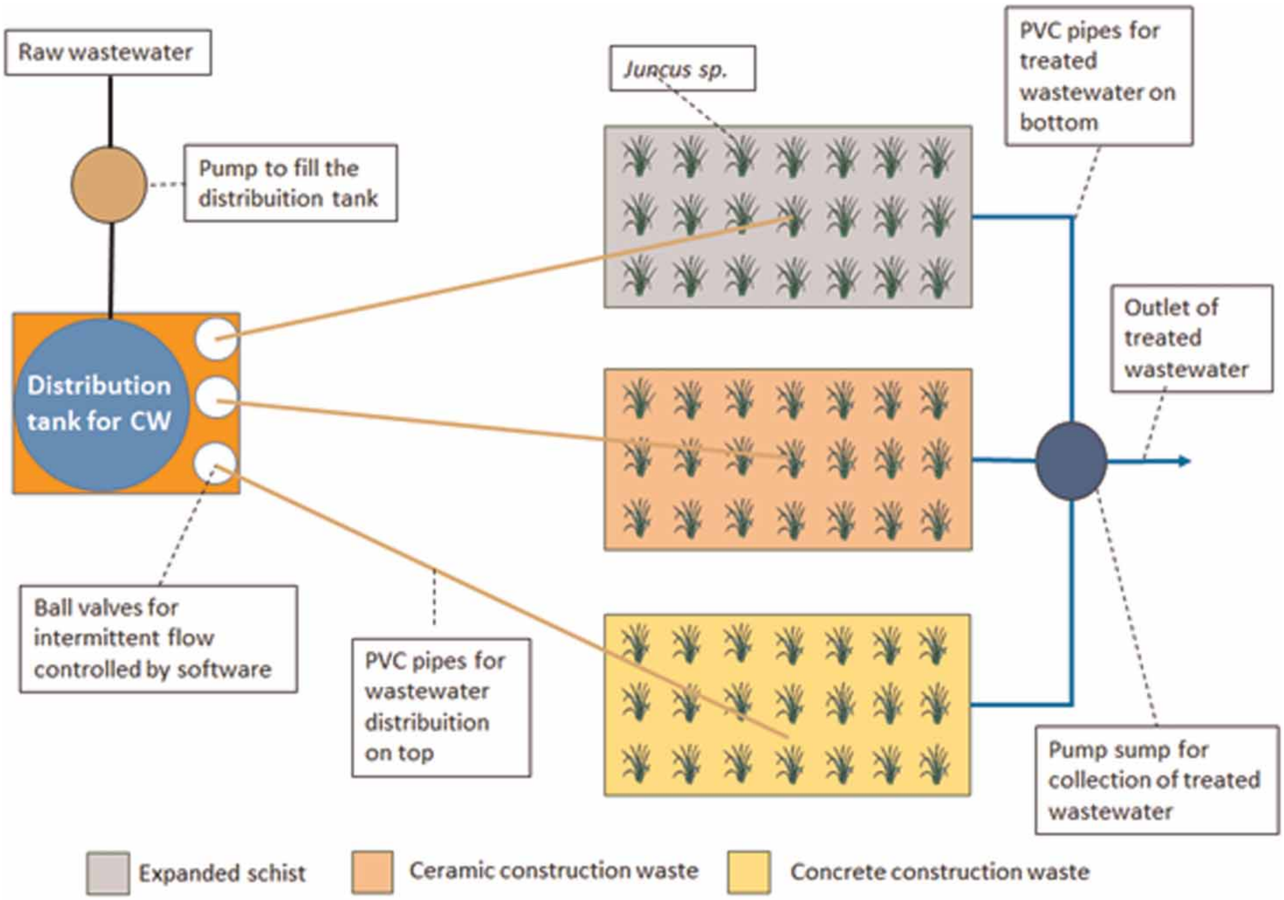
This paper evaluates the performance of raw domestic sewage treatment by a single-stage vertical-flow constructed wetland (VFCW) installed in Northeastern Brazil, where sanitation coverage is low. Biological and physicochemical parameters were monitored for 1 year to evaluate the system's performance. The impact of factors such as operational cycle and filter media on VFCW pollutant removal efficiencies was investigated. The means of removal efficiencies of chemical oxygen demand (COD), biological oxygen demand (BOD), and ammonia were 74.2, 87.9, and 82.1%, respectively. A statistically significant influence ($p < 0.05$) of substrate material on COD and ammonia removal efficiency was found. Ceramic construction waste media achieved the best performances compared with the traditionally used material and concrete construction waste. Operational cycles of 3.5/7 and 7/14 days of the feeding/resting period did not present a statistically significant influence ($p < 0.05$) on pollutant removal efficiencies. The single-stage VFCW pilot plant achieved a better global treatment performance than other VFCW reported in the literature; however, it showed a limitation in removing TS. The reduced installation costs, in addition to operation and maintenance simplicity, indicate a potential for single-stage VFCW applicability in the sewage treatment of housing units and small communities in Brazil and possibly in other developing countries in tropical areas.

Key words: ceramic construction waste, concrete construction waste, decentralized treatment, domestic wastewater, feeding operation

HIGHLIGHTS

- The single-stage vertical-flow constructed wetland (VFCW) overall means of removal efficiencies of COD, BOD, and ammonia were 74.2, 87.9, and 82.1%, respectively.
- Filter media variation statistically influenced the removal efficiencies of COD and ammonia.
- The operational cycles did not statistically influence the removal of pollutants.
- The single-stage constructed wetland has a potential for application in housing units and small communities in tropical areas.

GRAPHICAL ABSTRACT



INTRODUCTION

The World Health Organization (WHO) estimates that 4.2 billion people in the world do not have access to safe sanitation services (WHO 2021). The situation is not different in Brazil, where despite significant advances in the sanitation sector, only 55% of the Brazilian population has access to sewerage service and just 50.8% of the sewage produced in the country undergoes treatment (SNIS 2020). According to the Brazilian National Sanitation Information System (SNIS), the sanitation coverage is even lower in the Brazilian North and Northeast regions, where merely 13.1 and 30.3% of the sewage are collected, respectively (SNIS 2020).

The benefits of access to sanitation services on improving living standards are well known, such as a reduction in health risks, promotion of better education, and increase in the productivity of the labor force (Hutton & Chase 2017). Safe sanitation also helps to improve the quality of surface waters with attendant benefits for the environment (e.g. the functioning of ecosystems and biodiversity), as well as for economic sectors that depend on water as a resource (e.g. fishing, agriculture, and tourism) (OECD 2020).

Many strategies can help to improve sanitation coverage, and among them, the adoption of decentralized (onsite) wastewater treatments, which are suitable for very diverse conditions, requires moderate investment costs with reduced operation and maintenance (Arias *et al.* 2020). Due to their favorable economical and functional features, septic tanks are the most popular single-unit wastewater treatment in developing countries (Sharma *et al.* 2014). In addition to septic tanks, anaerobic filters are traditionally used in Brazil. Not only conventional systems, but also alternative treatment technologies such as constructed wetlands (CWs) are feasible for developing tropical countries, but these are still less explored (Silveira *et al.* 2015).

CWs are engineered systems concepted to utilize the natural processes involving vegetation, soils, and microorganisms to treat wastewater (Vymazal 2010). The main treatment mechanisms related to CWs are filtration, microbial organic matter degradation, nutrient adsorption by macrophytes, and soil adsorption (Mendonça 2011). The systems are composed of a waterproof layer to prevent wastewater from mixing with groundwater; media to intercept significant pollutants through sedimentation, filtration, and adsorption (Lu *et al.* 2016); water-resistant plants and hydraulic installations.

CWs are suitable solutions for decentralized systems in places with warm temperatures, extensive radiation hours, and field availability (Machado *et al.* 2017). The versatility afforded by different combinations of CW components makes the system interesting for application in various regional conditions, including parts of Brazilian territory, with the possibility of using local materials that are easily found and available in remote areas (Zanella *et al.* 2010). The most common CW media materials, or support matrix, are zeolite (Lizama-Allende *et al.* 2021), vermiculite, gravel, limestone (Lizama-Allende *et al.* 2021), coal ash, slag, grit and soil, clay minerals, and some industrial byproducts (Lu *et al.* 2016). Alternative materials have also been investigated, such as tile and bamboo (Zanella *et al.* 2010), biochar and oyster shell (Saeed & Khan 2019), and polystyrene foam (Khalifa *et al.* 2020).

Recycled aggregates are considered an interesting source for wastewater treatment not only for extending the utilization of construction and demolition waste (Li *et al.* 2021) but also for their pore structures and the composition of mineral elements such as Al, Fe, and Ca (Shi *et al.* 2017). However, only a few studies refer to construction waste materials as media to CW, such as recycled bricks (Shi *et al.* 2017; Saeed *et al.* 2018; Saeed & Khan 2019), and recycled aggregates from concrete structures (Li *et al.* 2021).

The vertical-flow constructed wetland (VFCW) configuration, which treats raw domestic wastewater without a primary stage, is known as the 'French system', also known as French VFCW (FVF) (Parde *et al.* 2021) and the French system of vertical-flow treatment wetlands (FS-VFTW) (Lombard-Latune *et al.* 2018). A study conducted on more than 80 pilot plants in France showed that the system efficiently removes chemical oxygen demand (COD), SS, and TKN and generally needs sludge management only after 10–15 years (Molle *et al.* 2005). Modifications to the 'French system' have been suggested to adapt it to tropical climates (Molle *et al.* 2015), such as the use of a single vertical-flow CW stage with a saturated bottom layer called the 'compact French system' (Silveira *et al.* 2015). It differs from the classic VFCW French design, which consists of two stages of unsaturated VFCW in series, each composed of two or three beds, and sequentially fed in batch operation mode with wastewater (Paing *et al.* 2015). It can be especially attractive for the North and Northeast regions of Brazil where a low percentage of the population is provided with access to a sewage network (Machado *et al.* 2017).

Brazil is a country with a large territorial area and has a climate favorable to biological processes. Moreover, the country has a deficit in terms of sewage network, as previously mentioned, and being an economically emerging nation, it faces problems with regard to the accumulation of waste from civil construction. Given these challenges, this work proposed an adapted configuration of a single-stage VFCW to treat raw wastewater using construction waste and investigated the influence of feeding mode and different construction waste substrates on effluent quality.

METHODS

Study area

The pilot plant evaluated in this work was installed in the wastewater treatment station of Mangabeira, the city of Joao Pessoa (PB), which is located on the coast of Northeastern Brazil (7 °11′18.45″ S, 34 °50′11.37″ W). The Mangabeira station serves a population of approximately 100,000 inhabitants. The municipality experiences high temperatures all year round, ranging, on average, between 23.7 and 29.8 °C. The wet season is from March to August, and the dry season is from August to February. The annual average precipitation and humidity are 1914 mm and 76%, respectively. The Köppen Classification for the climate is Am. The experiments were carried out from the April to March period.

Design of the pilot plant

In this work, an adapted system from the single-stage VFCW (compact French system) was used to simulate the treatment of domestic sewage for a housing unit. It consisted of a single-stage treatment with three parallel filter beds, batch fed in alternative cycles of feeding, and resting periods to prevent clogging (Prost-Boucle & Molle 2012).

The surface per capita area rate of 1.25 m^2 was used for dimensioning the adapted VFCW according to the compact French system. The rate value was chosen based on the recommended range of 1.2–1.5 m^2 from Paing *et al.* (2015) and on the recommended first stage area of 1.25 m^2 from Molle *et al.* (2005). The system was designed for a population equivalent of six people to producing 150 L d^{-1} of wastewater per person and 900 L d^{-1} in total. Using the criteria mentioned above, a total surface area of 7.5 m^2 was established for treatment. Each bed was built with a surface area of 2.5 m^2, with the following dimensions: 2.5 m × 1.0 m × 1.4 m depth (being 1.2 m to the filtering material and a 0.2 m free zone for sludge accumulation on top).

The feeding system was made of PVC pipes to distribute the influent over the surface. The drainage system was made of a network of perforated pipes (Ø100 mm) placed at the bottom of the bed and connected to several vertical pipes for aeration. An intermediate perforated pipe was added above the third layer of media in the middle of the filter depth to enhance the aeration.

Media and vegetation

Each bed was filled with different material as expanded material. The first bed was filled with the traditional material of expanded schist (bed 1), the second was filled with ceramic construction waste (bed 2), and the third was filled with concrete construction waste (bed 3). All three beds were complementarily filled with supporting material. The layers' depths were adapted from Paing *et al.* (2015), from bottom to top: 0.2 m of gravel 1 (Ø = 10–20 mm), 0.2 m of gravel 0 (Ø = 4–10 mm), 0.2 m of expanded material (support media for biofilm growth) (Ø = 0.5–4 mm), 0.3 m of gravel 0 (Ø = 4–10 mm), and 0.3 m of expanded material (support media for biofilm growth) (Ø = 2–4 mm). The bed cross section and the expanded materials are illustrated in Figures S1 and S2.

The construction waste was acquired from a construction site nearby. The filtering material for the three bed units was crushed in a solid waste processing plant in the municipality and transported to the WWTP site. The degree of cleanliness was low before the application of the material in the VFCW.

In this study, *Juncus* spp. ('Junco') was planted in all three beds in the spatial distribution of 8 units/m^2. The choice of macrophyte depended on the following criteria: fast biomass growth, adaptability to wet soil, local availability, and previous studies (Machado *et al.* 2017).

Description of the VFCW operation

The VFCW was fed with domestic wastewater from the WWTP Mangabeira. The raw wastewater was pumped after bar screen and grid removal to a distribution tank of 0.25 m^3. From the distribution tank, the raw wastewater was distributed to the VFCW beds through three pneumatic ball valves, controlled by software.

Two batch operation cycles were investigated. The first one consisted of a feeding period of 7 days, followed by a resting period of 14 days (Paing *et al.* 2015). The second one consisted of a feeding period of 3.5 days, followed by a resting period of 7 days (Prost-Boucle & Molle 2012). In the feeding period, the bed received five daily loads of 0.072 m^3 m^{-2} (180 L) each, every 3 h (from 6 a.m. to 6 p.m.), corresponding to a daily hydraulic load of 0.36 m d^{-1}.

The filters were put into operation in autumn with the first cycle set. After 3 months, the second cycle was implemented and operated for a 4-month phase. Considering that cycle 1 was first investigated in the rainy local season, the system was operated again for 3 months in the dry season to reduce the interference of the rainfall regime in the cycle 1 performance. Figures S3 and S4 illustrate the CW system in both operational cycles.

Monitoring

The influent and effluent samples were collected once a week during 12 months of the monitoring campaign. Physicochemical and biological analyses were conducted according to the Standard Methods for the Examination of Water and Wastewater (AWWA/APHA/WEF 2017). The monitored parameters were pH, conductivity, temperature, total solids (TS), total fixed solids (TFS), total volatile solids (TVS), thermotolerant coliforms, biological oxygen demand (BOD), chemical oxygen demand (COD), and ammonia. Table S1 shows the analytical methods applied for the determination of each parameter. The removal efficiency was calculated using the following equation:

$$Removal\ (\%) = \frac{C_i - C_f}{C_i} \times 100$$

where C_i and C_f are the pollutant concentrations in the influent and effluent, respectively.

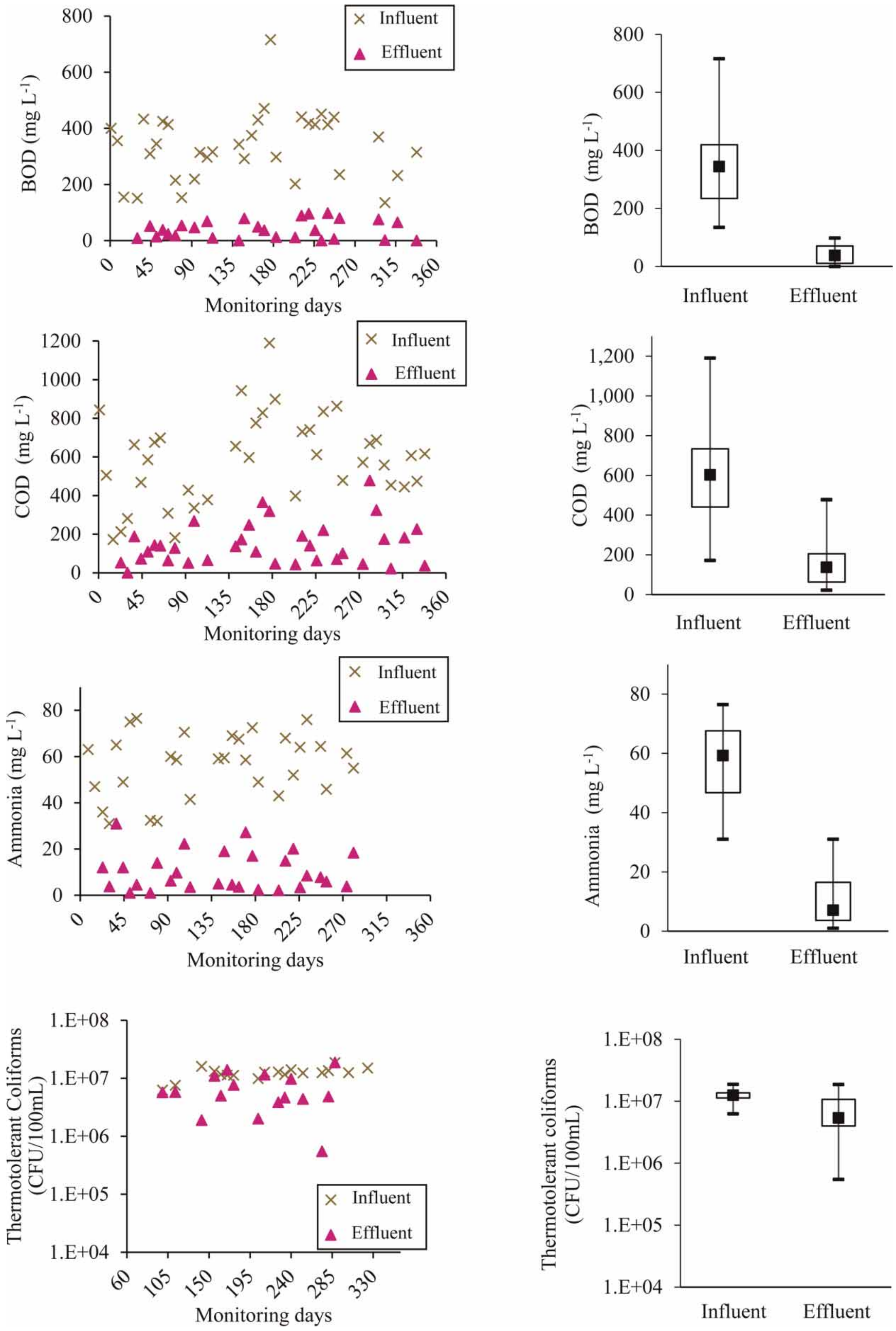


Figure 1 | Variation of pollutant concentration through the operation period (left) and boxplots (right) for single-stage VFCW influent and effluent.

RESULTS AND DISCUSSION

Global removal efficiencies

Figure 1 and Table 1 summarize the data from the global operation, including both operational cycles and the three bed units. The data describe the overall results achieved after 12 months of operation either by the first operational cycle (7/14 days) or by the second operational cycle (3.5/7 days). The global results consist of the average performance achieved for the three beds built in parallel, each with a different expanded material. During the first operational cycle, the alternation between beds was conducted once a week, and during the second operational cycle, the alternation was conducted twice a week.

The single-stage VFCW monitored in this study met the criteria for BOD according to the Brazilian standard for the sewage system, of 120 mg L^{-1} maximum concentration or 60% minimum efficiency (when the maximum concentration value is not met). It can be observed that the system was able to maintain stable BOD concentrations on effluents even for a wide variation of raw wastewater BOD loads entering the system. The average organic load applied was 122 g m^{-2} d^{-1}.

The single-stage VFCW produced an effluent with a higher concentration of TS than raw sewage. The possible cause for the increase in solids in the VFCW effluent is the release of organic matter from the plant roots (Decezaro 2016; Rodrigues 2016) or from the filter media due to the low degree of cleanliness observed after crushing the materials to the recommended sizes. Hence, the degree of cleanliness of supporting material should be better cared for in further replications. Also, other plant types could be tested, such as *Pennisetum purpureum* and *Cynodon spp.*, which are native to Brazil and were found to achieve better results in the removal of solids and other wastewater pollutants (Machado *et al.* 2017).

The influent thermotolerant coliforms were 1.21×10^7 MPN 100 mL^{-1}, which is within the range for typical domestic wastewater, of 10^6–10^{10} MPN 100 mL^{-1} (Jordão & Pessoa 2005). The average effluent removal efficiency of 57% was lower than that reported in the literature for CW, which ranged between 86 and 99% (Amorim *et al.* 2019).

A good removal performance of BOD, COD, and ammonia was observed in comparison with the results reported in the literature for VFCW (Table 2). Mean removal efficiencies of BOD and COD were slightly higher than observed by another

Table 1 | Single-stage VFCW influent and effluent average concentration and removal efficiency for different parameters, pH, and temperature (n = number of samples)

Parameter (mg L^{-1})	Influent	SD	Effluent	SD	Efficiency (%)
TS (mg L^{-1})	565 (n = 29)	134	685 (n = 27)	200	(-) 21.2
TVS (mg L^{-1})	288 (n = 29)	103	214 (n = 27)	88	25.7
BOD (mg L^{-1})	338 (n = 34)	119	41 (n = 26)	32	87.9
COD	589 (n = 38)	225	152 (n = 33)	108	74.2
Ammonia (mg L^{-1})	57 (n = 30)	13	10 (n = 28)	8	82.1
Thermotolerant coliforms (MPN 100 mL^{-1})	1.21×10^7 (n = 18)	2.83×10^6	5.24×10^6 (n = 16)	4.87×10^6	57 (0.36 log)
pH	7.36 (n = 36)	0.18	6.89 (n = 33)	0.70	–
Temperature	25.6 (n = 36)	1.98	25.77 (n = 33)	2.07	–

Table 2 | Pollutant removal efficiency from VFCW reported by other studies

	Place	BOD (%)	COD (%)	Ammonia (%)	References
Two-stage VFCW	Goa, India	84	90	82	Yadav *et al.* (2018)
Two-stage VFCW	France	>90	>85	–	Paing *et al.* (2015)
Single-stage VFCW	France	>90	>80	–	Paing *et al.* (2015)
Single-stage VFCW	Savoie, France	>85	>80	>30	Prost-Boucle & Molle (2012)
Single-stage VFCW	Greenhouse	–	47[a]	47	Silveira *et al.* (2015)
VFCW	Viçosa, Brazil	–	59.6	44.5	Sarmento *et al.* (2013)
Single-stage VFCW	Belo Horizonte, Brazil	79	72	56	Lana *et al.* (2013)
Single-stage VFCW	João Pessoa, Brazil	87.9	74.2	82.1	This study

[a]dCOD.

study with single-stage VFCW, of 79 and 72%, after batch loads every 2 h (Lana *et al.* 2013). The ammonia removal rate achieved best values compared with those of other studies with single-stage VFCW in France and Brazil (Table 2). The BOD removal rate in this study outperformed a two-stage VFCW reported in India (Yadav *et al.* 2018). The advantage of switching from the 'compact VFCW' to the classic system was also described in a study comparing 169 full-scale French systems of VFCW (Paing *et al.* 2015). It is important to note, however, that removal rates are highly dependent on the system configuration and other parameters.

Factors affecting removal efficiencies

The analysis of variance (ANOVA) was conducted by using the statistical method of GT-2 (Sokal & Rohlf 2013), at a 5% significance level, to investigate the influence of different supporting media and different operation cycles on single-stage VFCW pollutant removal efficiencies. By the definition of the method, when bars are parallel for every set of data, the data do not differ statistically.

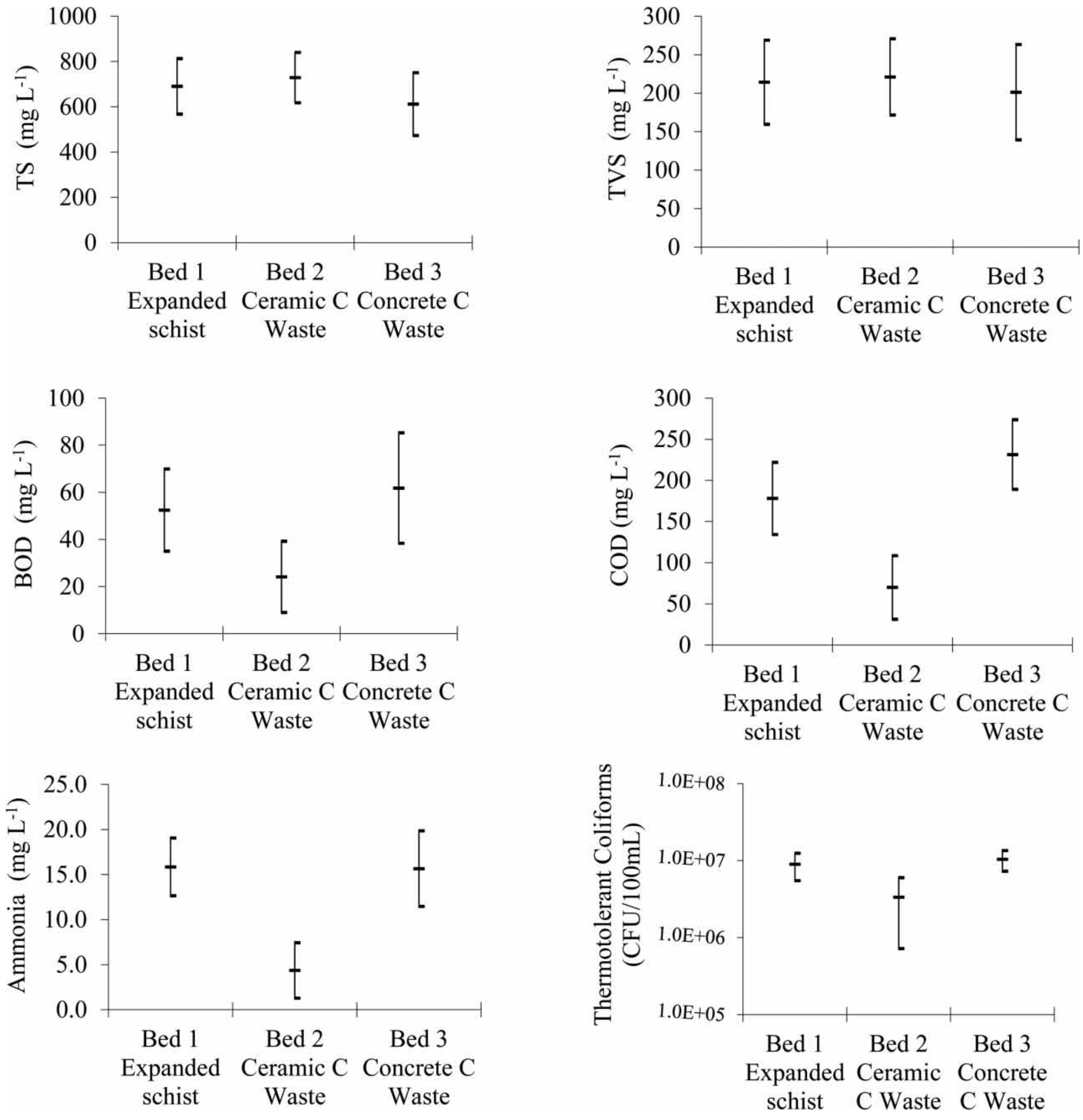


Figure 2 | ANOVA graphs by the GT-2 method were applied for each bed filled with different media (expanded schist, ceramic waste, and concrete waste) for TS, TVS, BOD, COD, ammonia, and thermotolerant coliforms.

Media to support biofilm growth

The bed filled with ceramic construction waste (bed 2) performed better than the other beds filled with expanded schist (bed 1) and concrete construction waste (bed 3), but the difference was statistically significant ($p < 0.05$) only for COD and ammonia removals (Figure 2). Best removal efficiencies of COD and ammonia were also achieved by CW using alternative media (Khalifa *et al.* 2020). An advantage on COD removal was also observed using recycled aggregates from construction and demolition waste as wetland substrates in comparison with the traditional matrix (Li *et al.* 2021). The advantage on ceramic waste can be justified by the high porosity and good adsorption properties of the material, as well as its chemical composition (Saeed *et al.* 2018; Saeed & Khan 2019; Li *et al.* 2021), which facilitates microorganism and plant growth in CW (Shi *et al.* 2017).

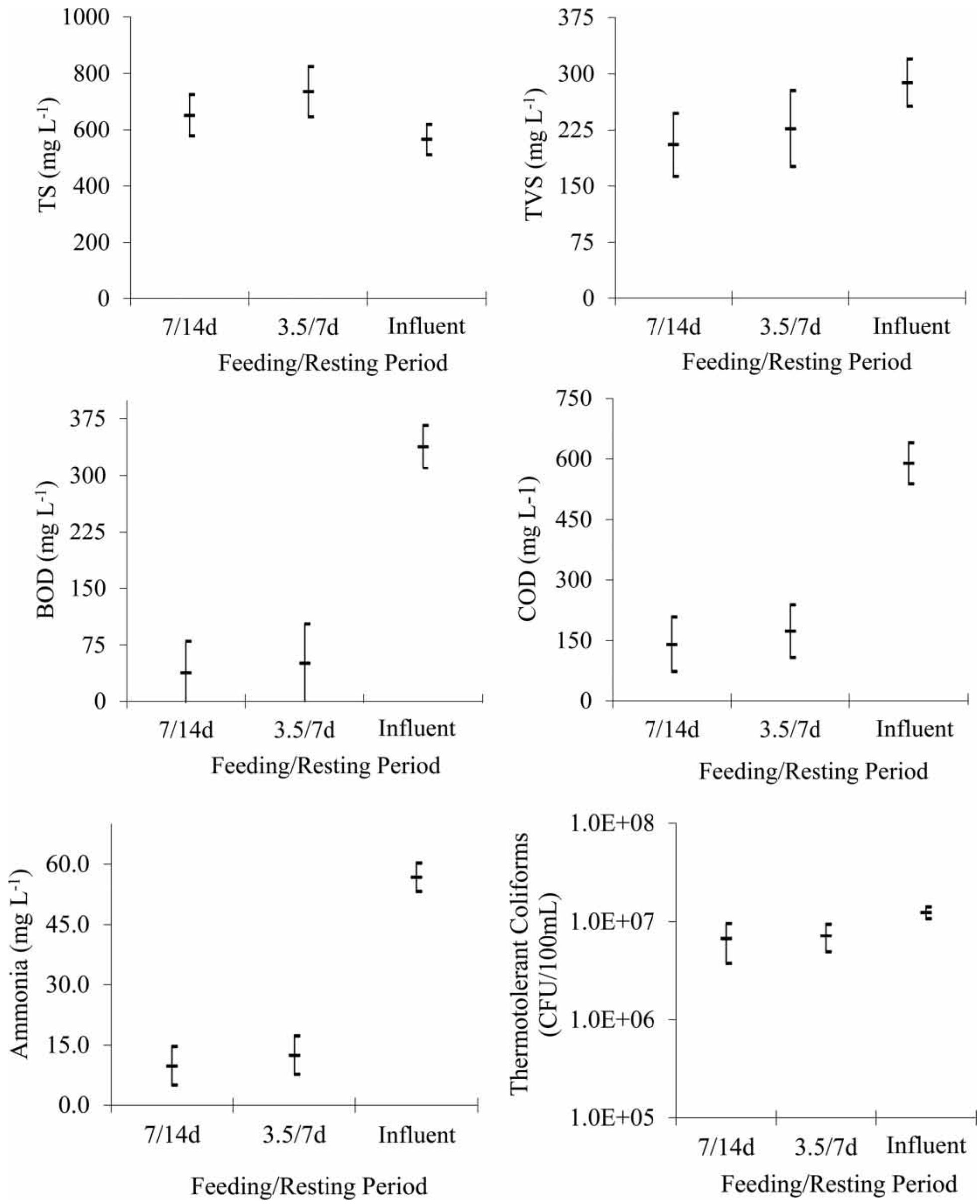


Figure 3 | ANOVA graphs by the GT-2 method were applied for the influent and effluent of each operation cycle of the feeding/resting period (7/14 days, 3.5/7 days) for TS, TVS, BOD, COD, ammonia, and thermotolerant coliforms.

Operation cycle (feeding/resting period)

The effect of two different operation cycles on the single-stage VFCW treatment efficiency was investigated. The feeding/resting cycles of 7/14 days and 3.5/7 days did not differ in terms of statistical significance for the removal of TS, TVS, BOD, COD, ammonia, and thermotolerant coliforms, as shown in Figure 3. The influent concentrations were displayed to contrast with the VFCW results. Based on these results, the 7/14-day operational cycle is recommended because it can be simpler to operate if the alternation from one bed to the other is made manually, in contrast to the 3.5/7-day cycle, which requires a bed feeding change twice a week. In economically developing countries, operational simplicity and cost-saving are vital aspects to be considered (Lana *et al.* 2013).

CONCLUSIONS

The single-stage VFCW is an efficient compactly designed system and a low-cost alternative for raw sewage treatment in single houses or small communities. The single-stage VFCW pilot system investigated in this work was able to achieve, after a 12-month monitoring campaign, global removal efficiencies of 74.2, 87.9, and 82.1% for COD, BOD, and ammonia, respectively. The treatment system met the Brazilian wastewater discharge requirement for BOD. However, the system showed a limitation for TS reduction, which should be considered for further replications of the proposed configuration.

Construction waste stood out as a possible and efficient substitute for expanded material in CW systems. Ceramic construction waste performed better than traditional material, such as expanded schist, with a statistically significant effect ($p < 0.05$) for COD and ammonia removal. The two types of operation cycles (7 days' feeding/14 days' resting and 3.5 days' feeding/7 days' resting) produced effluents with similar quality, with no statistically significant effect on pollutant removal. Thus, for a simple operation, the 7/14-day cycle was recommended.

The single-stage solution presented in this work is a great potential option for onsite domestic wastewater treatment for a population without any sewerage service such as in Brazil and other countries, especially in tropical weather zones.

Further research should be conducted in real-scale plants implemented in houses or communities without access to wastewater treatment, with a longer monitoring period, for a better understanding of the effect of supporting media and macrophytes on effluent quality. Finally, it is important to study the life cycle assessment of the 'compact' VFCW to compare its possible environmental benefits with other low-cost wastewater treatment solutions.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

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

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