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Performances of two pilot decentralized wastewater treatment plants used to treat low-strength wastewater

Julliana Alves da Silva[a,*], Arnaldo Sarti[b], Gustavo Henrique Ribeiro da Silva[a]

[a] *Department of Civil and Environmental Engineering, The College of Engineering Bauru, UNESP - Universidade Estadual Paulista, Av. Eng. Luiz Edmundo Carrijo Coube, 14-01, 17033-360, Bauru, SP, Brazil, Tel. +55 14 3103 6000; emails: jualves.bio@gmail.com (J.A. da Silva), gustavoribeiro@feb.unesp.br (G.H.R. da Silva)*

[b] *Department of Biochemistry and Chemical Technology, Institute of Chemistry, UNESP – Universidade Estadual Paulista, Campus Araraquara, Rua Prof. Francisco Degni, 55, 14800-900, Araraquara, SP, Brazil, Tel. +55 16 3301 9860; email: arnaldosarti@iq.unesp.br*

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ABSTRACT

The performances of an anaerobic/aerobic baffled reactor (AABR) and a horizontal subsurface flow constructed wetlands (HFCW) have been investigated. In this study, both systems were operated in parallel using the same source of domestic low-strength wastewater (0.06–0.61 kg COD m^3 d^{-1}). The inlet concentrations, expressed as chemical oxygen demand (COD), ranged from 105 to 381 mg COD L^{-1}. The outlet concentrations ranged from 12 to 147 mg COD L^{-1} in the AABR and from 7 to 88 mg COD L^{-1} in the HFCW. The AABR and HFCW achieved 78% ± 9% and 82% ± 9% COD average removal rates, respectively. To compare the results, a statistical test (significance level of 0.05) was used and showed no significant difference between the systems in terms of organic matter and total suspended solids (TSS) removal. In addition, this study addressed energy costs and treatment capacity per area for both wastewater treatment systems that were studied independently with capacities for 20 habitants, and showed lower energy consumptions per month when compared with a domestic electric shower generally used by a sample Brazilian family consisting of four members.

Keywords: Anaerobic baffled reactor; Aerobic chamber; Horizontal subsurface flow constructed wetlands; Sanitary wastewater; Energy cost

1. Introduction

Wastewater treatment is essential to ensure public health and environmental quality. Unmanaged wastewater can be a source of pollution and a hazard to the health of human populations and the environment alike. Unfortunately, billions of people throughout the world do not have access to adequate wastewater treatment systems and as a consequence discharge large volumes of untreated wastewater into surface waters. Approximately 80%–90% of all wastewater generated in developing countries is discharged directly into surface water bodies [1].

The situation in Brazil is equally problematic, as demonstrated by the number of cities that lack any kind of wastewater treatment. According to the National Sanitation Information System [2], only 48.6% of Brazil's population has access to wastewater collection, and a mere 39% of collected wastewater is treated.

Due to growing concerns regarding the quality of the environment and water resources, researchers have been dedicated to search for alternatives that can meet the needs of developing countries and areas with poor wastewater treatment, including decentralized wastewater treatment (DEWAT). DEWAT is more appropriate for low-density communities and varying site conditions and is more cost-effective than conventional practices [3]. There are different types and

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* Corresponding author.

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configurations of DEWAT such as septic tanks, anaerobic baffled reactors, anaerobic filters, anaerobic and facultative pond systems and constructed wetlands (CW).

Anaerobic baffled reactors (ABRs) have been reported to be a promising solution for treating domestic [4,5] and other types of wastewater [6]. An ABR was developed in the early 1980s by McCarty [7] at Stanford University and was described as a series of upflow anaerobic sludge blanket (UASB) reactors [8] interconnected in chambers. That configuration incorporates the advantages of UASB reactors that include resistance to shock loads, high biomass retention capacity over long periods [9] and high treatment rates thanks to self-immobilization of the microbial consortium in the form of granules that consist of different types of bacteria and organisms per gram of biomass [10].

UASB reactors are already consolidated to treat sanitary sewage, but it is known that that configuration only achieves 50%–80% organic matter removal in terms of chemical oxygen demand (COD) [11], does not remove nutrients and often requires combined systems to achieve the percentage of organic matter removal required by Brazilian legislation. In this case, the use of ABRs becomes advantageous because they can achieve 85%–90% organic matter removal in terms of COD [11] and present the possibility of removing nutrients by only aerating one of the final chambers.

Using an eight-chamber ABR, Gopala Krishna et al. [12] achieved removal rates of 90% for COD when treating low-strength soluble wastewater (COD ≈ 500 mg L^{-1}). In a modified ABR, Bodkhe [13] achieved 84% COD removal and 87% biochemical oxygen demand (BOD_5) removal when treating municipal wastewater at a hydraulic retention time (HRT) of 6 h. Silva et al. [14] reported a maximum COD removal rate of 92% and average removal of 78% in a three chamber ABR with an additional aerobic chamber (AC) when treating low-strength domestic wastewater using four different HRTs. These results showed the potential of ABRs to treat different kinds of wastewater.

Another DEWAT that has received a large amount attention is CWs. CWs having high pollutant removal efficiencies are easy to operate and maintain, have low costs, good potential for water and nutrient reuse, tolerance to high variability, and function as significant wildlife habitats [15]. CWs have gained popularity in the last four decades as an alternative to conventional treatment and are considered to be cost-effective and sustainable for wastewater treatment [16]. Based on water flow regime and type of macrophyte growth, CWs can be classified into three groups: free water surface flow, subsurface flow, and hybrid systems [17].

In subsurface flow CWs, wastewater is transferred through filtering media and flows in the porous section (substrate) in a horizontal or vertical path, and contaminants are removed mainly by physical mechanisms such as filtration and sedimentation and biochemical interactions such as microbial degradation [18].

The development of CWs has received a large amount of attention, and they have also been significantly applied to treat several kinds of wastewater [19]. Zurita et al. [20] investigated the use of four commercially valuable ornamental plant species in two types of subsurface flow wetlands in a tropical area in Jalisco, Mexico, fed with domestic wastewater. The removal rates for the horizontal subsurface flow CW were 77.9% for BOD_5, 76.3% for COD and 82% for TSS.

The aim of this study was to evaluate the behaviors of the two types of decentralized treatment systems employing a pilot-scale anaerobic/aerobic baffled reactor and a horizontal subsurface flow CWs used to treat low-strength wastewater from a university campus. The objective of comparing the applications of two such unique systems was to verify those applications to the same wastewater on a pilot scale.

Several ABR configurations combined with aerobic systems have been presented in the literature, but little is known about the use of additional ACs.

2. Materials and methods

2.1. Experimental setup

This study was carried out in a pilot-scale wastewater treatment system constructed on the campus of the São Paulo State University (Bauru, São Paulo, Brazil). The campus generates 7,300 L d^{-1} of diluted domestic sewage that is diverted into secondary systems at specific flow rates (Table 3).

The system consisted of preliminary and primary treatment employing a metal screen (placed at a 45° angle relative to horizontal), settling and equalization tanks of 5,000 and 2,200 L, respectively, a storage tank (200 L), an anaerobic/aerobic baffled reactor (AABR) and a horizontal subsurface flow constructed wetlands (HFCW).

The AABR, the features of which are described in Table 1, consisted of three cylindrical anaerobic chambers (C1, C2 and C3) that were followed by an additional AC built using polyvinyl chloride (PVC) and an 80 L laminar settling tank (LST). The inner plates of the LST were made using plastic (placed at a 60 degree angle relative to horizontal). In the AC, two air microporous diffusers (10 μm) of conical shape were placed on the bottom of the chamber (75 mm diameter and 70 mm high) and connected to an air compressor that supplied the air. Air flow was controlled using a flow meter. The upper part of the AC was filled with bamboo rings (*Bambusa vulgaris)* used as inert supports for biomass immobilization; they were placed 50 cm below the top of the chamber, which had a height of 0.6 m and a diameter of 0.4 m. The total area used to construct the AABR was 2.0 m × 3.0 m.

The HFCW, the features of which are described in Table 2, consisted of a rectangular basin with dimensions 9.0 m × 4.5 m × 0.80 m (inner length, width and height) and a longitudinal slope of 1%, and the basin was filled with four different layers comprised of sand, gravel, styrofoam beads and crushed rock. The volume of the basin was 17.58 m^3 and the effective volume was 10.29 m^3. The plant species used was Vetiver grass (*Chrysopogon zizanioides*), and 90 seedlings were

Table 1
Characterization of the AABR chambers

Chamber	Specifications		
	Height (m)	Diameter (m)	Volume (L)
C1	0.90	0.6	405
C2	0.90	0.3	96
C3	0.90	0.3	96
AC	1.70	0.4	220

planted along the tank. To distribute the wastewater inside the wetlands, inlet and outlet devices were installed in the basin such that the distribution inside was equal throughout the support medium. The devices consisted of two 4.0 m PVC pipes of 100 mm diameters (drain lines) that were drilled on their bottoms along their entire lengths. The inlet pipes were set up at the beginning and at the top of the tank, and the outlet pipes were set up at the end and at the bottom of the tank.

The scheme of the experimental setup is presented in Fig. 1.

2.2. Operational conditions

Both systems were designed to treat the wastewater produced by 20 people, and the operational conditions are described in Table 3.

Table 3
Operational conditions of the AABR and HFCW

System	AABR	HFCW
Flow (L s^{-1})	0.026	0.032
HRT (h)	C1 3 C2 1.5 C3 1.5 AC 2.25 Total 8.25	88
Area for construction (m^2)	6.0 (2.0 × 3.0)	40.5 (9.0 × 4.5)
Operational period (d)	63	63
Treatment/capita (L d^{-1})	115	117

Table 2
Characterization of the HFCW bed

Layer	Specifications			
	Inner length (m)	Width (m)	Height (m)	Dimension of the particles (mm)
Sand	9.0	4.5	0.10	4.8
Gravel	9.0	4.5	0.20	12
Styrofoam beads	9.0	4.5	0.40	3 to 8

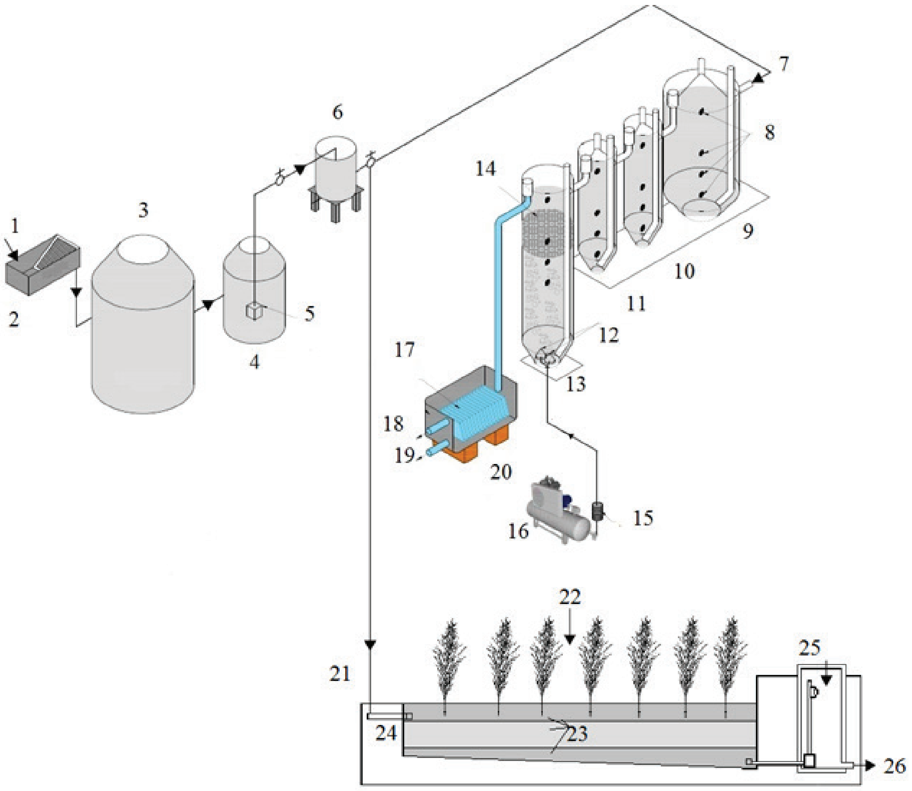

Fig. 1. Schematic diagram of the system: 1, raw wastewater; 2, screen; 3, settling tank; 4, equalization tank; 5, pump; 6, storage tank; 7, AABR inlet; 8, chamber sampling points (for the present study, the higher points were used); 9, chamber 1; 10, chamber 2; 11, chamber 3; 12, air diffusers; 13, anaerobic chamber; 14, bamboo rings; 15, air flow meter; 16, air compressor; 17, plastic plates; 18, AABR outlet; 19, sludge exit; 20, laminar settling tank; 21, HFCW Inlet; 22, Vetiver grass; 23, horizontal subsurface flow bed (sand, gravel, Styrofoam beads); 24, drain line; 25, outlet handle (for maintenance of the outlet box and samples collection); 26, HFCW outlet.

2.3. Sampling and analysis

Wastewater samples were taken once a week from the inlets and outlets of both systems. Sampling was usually performed at approximately 8 A.M. on each sampling date. The samples were analyzed for COD (5220 D method), pH (4500-H+B method), ambient temperature (thermometer), BOD$_5$ (5210 D method), TSS (2540 D method), and total coliforms (TC)/*E. coli* (9221 method) according to the Standard methods [21]. Tests for significant differences in wastewater quality between inlets and outlets for COD, BOD$_5$ and TSS removal efficiencies for each treatment were determined using paired t-tests at a significance level of 0.05 [22] for each set of data.

3. Results and discussion

In the specific case of domestic sewage (university campus) treated by the systems, the largest portion comes only from toilets and lavatories that were considered to be diluted with low organic loads and suspended solids in this case. However, there were in general effective variations in the parameters analyzed in the effluent samples, mainly in terms of COD, BOD and suspended solids. Because the systems received contributions only from toilets and lavatories, the variations were small but very perceptible throughout the operation. In the case of sewage from a university campus, the different activities carried out in the area generate sewage with characteristics slightly unlike those of regular domestic sewage; they vary strongly and unpredictably depending on the developed set of activities. The sewage in the present study was considered to be a complex type of low-strength wastewater characterized by low COD concentrations, high suspended solid fractions and organic load fluctuations. The COD and BOD$_5$ concentrations that were found agreed with Metcalf & Eddy, Inc. [23] as low-strength wastewater. Table 4 shows the average concentration parameters in the inlets and outlets of both systems.

The high suspended solid fractions did not reflect the sewage used for the experiment (27–71 mg TSS L^{-1}), which was interesting for the anaerobic and aerobic biomass in the AABR, because it was not inoculated. In this case, biological sludge was not removed in the AC during the period of operation. Table 4 shows the average concentration parameters for the inlets and outlets of both systems.

Table 4
Average and standard deviations (SD) of the parameters studied for the AABR and HFCW

Parameters	Inlet[a]	AABR outlet[a]	HFCW outlet[a]
COD, mg COD L^{-1}	214 ± 63	48 ± 25	47 ± 21
BOD$_5$, mg BOD$_5$ L^{-1}	85 ± 36	23 ± 11	38 ± 11
TSS, mg TSS L^{-1}	43 ± 28	4 ± 3	10 ± 10
pH	7.3 ± 0.2	7.3 ± 0.1	6.4 ± 0.18
Total coliforms, CFU 100 mL^{-1}	1.52×10^7	2.76×10^5	1.42×10^6
E. coli, CFU 100 mL^{-1}	3.27×10^6	1.01×10^5	3.45×10^5

[a] Average ± standard deviation calculated for nine samples at each point.

Both systems were operated in the mesophilic range at ambient temperatures of 27°C to 30°C. The pH values remained between 6.8 and 7.5 in the inlets, 6.9 and 7.7 in the AABR's outlet and 6.2 and 6.8 in the HFCW's outlet. No significant variations in pH were observed in either system, which were operated over a neutral range.

3.1. Removal of organic matter and suspended solids

Anaerobic digestion in anaerobic reactors removes organic matter and other pollutants through biological processes in the absence of oxygen, in which several communities of microorganisms present in the system cooperate to achieve the stable and self-regulated metabolism of organic matter, converting complex residues to simpler waste products such as carbon dioxide and methane [24]. In the case of the AABR used in this study, an AC was added, and with the addition of an aerobic process, the AABR could be considered to have been an activated sludge system.

In CWs, the stabilization and removal of organic matter occurs in a similar way. As wastewater passes through the root zone, organic matter is decomposed by microorganisms, which are placed in the middle of the bed filling material [25]. While crossing the support medium, the wastewater comes into contact with a mesh of anaerobic, aerobic and anoxic zones, where it is primarily treated by the microorganisms that develop there as well as by physico-chemical processes. Aerobic zones occur in the rhizosphere of macrophytes planted (roots and rhizomes), which introduce oxygen into the support medium from different sources, such as by the process of photosynthesis, through direct transport from the atmosphere or transport through the plant bodies [26].

The inlet wastewater concentrations, in COD terms, ranged from 105 to 381 mg COD L^{-1}. The outlet concentrations ranged from 12 to 147 mg COD L^{-1} in the AABR and from 7 to 88 mg COD L^{-1} in the HFCW. In terms of BOD$_5$, the inlet wastewater concentrations ranged from 36 to 162 mg BOD$_5$ L^{-1}, and the outlet concentrations ranged from 4 to 39 mg BOD$_5$ L^{-1} in the AABR and from 10 to 44 mg COD L^{-1} in the HFCW.

The COD average outlet concentrations were 48 ± 25 mg COD L^{-1} and 47 ± 21 mg COD L^{-1} for the AABR and HFCW, respectively, and the BOD$_5$ average outlet concentrations were 23 ± 11 mg BOD$_5$ L^{-1} and 38 ± 11 mg BOD$_5$ L^{-1} for the AABR and HFCW, respectively (Table 1). The organic matter concentrations decreased between the inlets and outlets in both systems, and the standard deviations of the COD and BOD$_5$ averages showed wide variations in the concentrations of the wastewater in relation to the source.

The COD average removal rates for the AABR and HFCW are shown in Fig. 2, the BOD$_5$ average removal rates for AABR and HFCW are shown in Fig. 3, and the TSS average removal rates for AABR and HFCW are shown in Fig. 4.

For the average inlet and outlet concentrations presented in Table 1, the AABR achieved a COD average removal of 79% ± 6%, with a maximal removal of 87%, a BOD$_5$ average removal of 80% ± 9%, with a maximum removal of 92%, and a TSS average removal of 93% ± 7%, with a maximum removal of 99%. The AABR removal rates of COD in the present study were similar to those found by researchers using

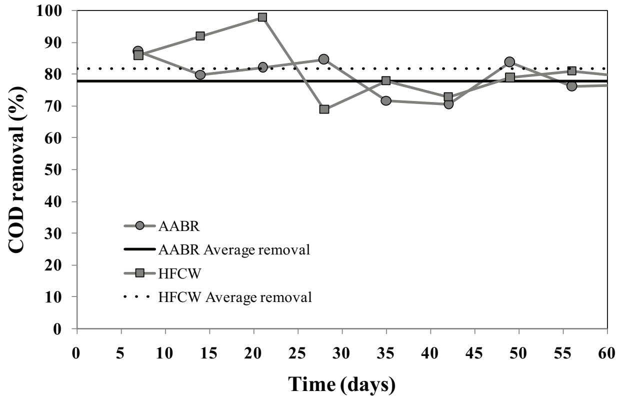

Fig. 2. COD removal rates and average removals for the AABR and HFCW.

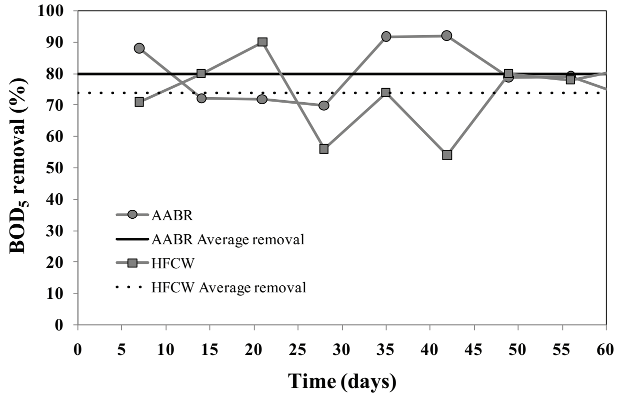

Fig. 3. BOD_5 removal rates and average removals for the AABR and HFCW.

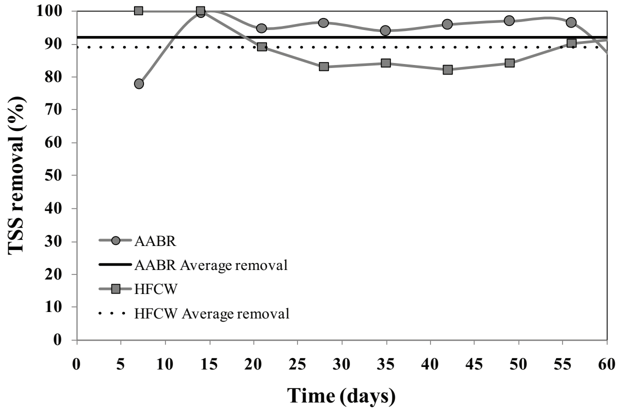

Fig. 4. TSS removal rates and average removals for the AABR and HFCW.

low-strength wastewater. Sarathai et al. [27] and Bae et al. [28] found similar COD removal rates using ABRs operated with low-strength wastewater. Lee et al. [29] found a COD average removal rate of 84%, but the authors related the high value to the secondary polishing system, which consisted of an anaerobic fluidized membrane bioreactor.

Regarding the contribution of the ACs, 53% of the COD average removal was achieved in the anaerobic chambers, and only the residual organic matter remained to be removed in the aerobic system. The ACs contributed an average COD removal of 26%, which is a low efficiency when compared with that for a conventional activated sludge system. This fact may be related to the low concentration of organic matter in the anaerobic outlet wastewater. These removal percentages also may be related to solid retention in the chamber.

Hahn and Figueroa [30] used a pilot scale ABR that consisted of four sequential chambers constructed with PVC pipes with a total hydraulic volume of 869 L to treat 1.728 L d^{-1} of domestic wastewater with an influent COD averaging 760 ± 190 mg L^{-1}. Their average COD removal was 43% ± 15%, which was much less than for the AABR, even when treating more concentrated wastewater. The BOD_5 average removal rates were also lower than those for the AABR: 47% ± 15% and 70% ± 18%, respectively. In this case, the higher COD removal rates reached by the AABR could be explained due the operating ambient temperatures (27°C–30°C) during the monitoring period, as the other system was operated at temperatures between 12°C and 23°C.

In this study, the HFCW system achieved an average COD removal rate of 70% ± 18%, with a maximum removal of 98%, an average BOD_5 removal rate of 74% ± 12%, with a maximum removal of 90%, and an average TSS removal rate of 83% ± 16%, with a maximum removal of 100%. According to Sundaravadivel and Vigneswaran [31], CWs generally are known to perform very well when compared with BOD_5 and COD removals. Calijuri et al. [32] registered average removals of 80% and 60% for BOD_5 and COD, respectively, in an HFCW filled with crushed rock and plant species *Typha* sp. and *Brachiaria* sp. The domestic wastewater treated in that system was a UASB effluent that had low BOD_5 concentrations (70 mg L^{-1}). The authors concluded that the system promoted high complementary removals, regardless of the operation or phase considered, and rarely produced effluents with concentrations higher than 15 mg BOD_5 L^{-1} and 20 mg TSS L^{-1}. In the present study, the average removal rates were similar to those in Calijuri et al. [32], although the HFCW affluent was not pre-treated as in Calijuri et al. [32], which in the present study performed better, obtaining COD average removal rates of 82% ± 9%.

Comparing both systems used in this study, the AABR was seen to be as efficient as the HFCW for the removal of organic matter and suspended solids, with no significant differences in terms of COD, BOD_5 and TSS, demonstrating their effective capacity to remove organic matter, even when fed with low-strength wastewater.

The organic matter removal and the outlet concentrations, in terms of BOD_5, from both systems met the Sao Paulo State legislation standards [33] for the control of effluent discharge that standardizes a maximum limit of 60 mg BOD_5 L^{-1}, with an 80% removal rate.

3.2. Total coliforms and E. coli removal

The TC and *E. coli* average concentrations in the treatments used in this research are presented in Table 1. The TC and *E. coli* average concentrations in the inlet were 106 and 107 CFU 100 mL^{-1}, respectively. The reduction in the number of TC and *E. coli* was 2.0 $\log_{10}$ in the AABR. The TC removal rate in the HFCW was 3.0 $\log_{10}$ and that for *E. coli* was 2.0 $\log_{10}$. From the analysis of TC and *E. coli*, the AABR and HFCW systems were found to have low removal rates (2.0–3.0 $\log_{10}$).

The Brazilian National Council of Environment Resolution [34] states that the maximum concentrations of *E. coli* in treated effluents must be between 2.0×10^2 and 2.5×10^3 CFU 100 mL^{-1}, depending on the type of water body receptor. In this case, both the AABR and HFCW need a disinfection step to improve coliform inactivation.

3.3. Energy cost and treatment capacity per area

To compare the average daily energy power consumptions per habitant from the treatment systems, the energies consumed by the pumps used in both treatments and the air compressor, which provided air to the AC in the AABR, were calculated.

An air compressor with a motor power of 1.5 kW (Twister Bravo, model CSL 10/100) was used in this research. The air compressor started every 60 min, worked for approximately 10 min, and operated for a total of 4 h d^{-1}. Therefore, the daily power consumption was 6.0 kWh d^{-1} (consumption = motor power × time). The amount of energy consumed per month was 180 kWh (6.0 × 30 d). Following this calculation, the utilized pump had a motor power of 0.7 kW, worked for 2 h d^{-1}, and consumed 1.4 kWh d^{-1} and 42 kWh per month.

According to the Sao Paulo State Company of Energy Power and Light [35], the residential price for power in Bauru city, including taxes, is US$ 0.0781 kWh^{-1}. Using a flow of 1.6 L min^{-1}, the AABR had the capacity to treat wastewater for 20 habitants, yielding a per capita cost of US$ 0.86 per month. Because the two pumps used for each system were the same, the HFCW would have an operating cost of US$ 3.26 per month when treating wastewater for 20 habitants and an operational cost of US$ 0.16 per capita per month.

In the case of the AABR configuration used in this study, the AC was important as a polishing step for the effluent and removed an average of 55% of COD. Removing the chamber from the system would reduce operating costs but would also reduce efficiency. The HFCW, therefore, was proven to be more cost-effective because it had high removal rates at a lower cost without the need for tertiary treatment. To match the two systems, it is possible to add another type of tertiary treatment to the AABR or to connect the two systems, using the HFCW as a tertiary system, to increase the treatment efficiency, as HFCWs are commonly used to treat municipal and domestic wastewater as tertiary treatment stages [36].

The average daily consumptions of power per habitant for both treatment systems were compared with the energy power consumption of an electric shower with a motor power of 3.5 kW that is used by a family of four people, each of whom uses the shower for 10 min d^{-1} (Table 5).

The results in Table 2 indicate that the AABR and HFCW consumed less power when compared with an electric shower commonly used in a residence. This fact is evidence of the feasibility of using an aeration system comprised of an air compressor and a pumping system, which is easily found on the market and enjoys low maintenance.

Regarding treatment capacity, the AABR used an area of 6.0 m^2, and given the estimated treatment at a flow rate of 0.026 L s^{-1}, the total area would be 0.25 m^2 for 20 habitants. The HFCW treated 58 L m^2 d^{-1} in an area of 40 m^2, and for 20 habitants, the total area per capita would be 2.02 m^2. In this regard, the AABR is more advantageous than the HFCW because it can treat wastewater for the same number of habitants in a smaller area and is, therefore, more applicable in small areas such as residential condominiums, commercial areas and small rural areas.

4. Conclusions

The results (means) attained by the AABR and HFCW in terms of COD, BOD_5 and TSS removal showed the potential for these technologies as promising alternatives to treat low-strength domestic wastewater, being applicable for this type of wastewater and most likely for wastewater with higher organic matter concentrations. The application of the AABR and HFCW to low-strength wastewater only provided significant results in terms of COD, TSS and BOD_5, thus proving the feasibility of their use for that purpose. The main problem was the low removal rates of TC and *E. coli*, which can be solved using a disinfection step.

Based on the responses of the AABR and HFCW, it can be concluded that these systems can be used for the combined removal of COD, BOD_5 and TSS in order to meet the effluent emission standards. By combining anaerobic and aerobic stages in the AABR, the effluent was effectively polished in the presence of inert material in the aerobic zone. However, to make the newly developed technologies successful, in practice, AABR reactor operational strategies should be optimized to reduce energy consumption.

In the context of this project, the main goal was achieved with a possible solution to treat low-strength domestic wastewater using technologies and materials that are available in Brazil. Studies focused on scaling up these units and biologically removing nutrients (N and P) and coliforms to obtain suitable effluents under the emission standards required by Brazilian legislation are important now.

Table 5
Approximate consumption values (per capita d^{-1}) of the treatment systems and an electric shower

Equipment	Power (kW)	WT (h d^{-1})	Habitants	Consumption (kWh per capita d^{-1})
AABR (air compressor + pump)	2.2	6	20	0.03
HFCW (pump)	0.7	2	20	0.07
Electric shower	3.5	0.67	4	0.59

WT, working time.

Regarding the power consumption per month for each system, the HFCW was shown to have lower energy costs; the AABR consumed 180 kWh per month, with a total cost per capita of US$ 0.86 a month, and the HFCW consumed 42 kWh per month, with a total cost per capita of US$ 0.16 a month. However, it is possible to conclude that the more expensive operation of the AABR due to the air compressor can be solved using other types of tertiary systems, including the studied HFCW. Overall, the two wastewater treatment systems, which had capacities for 20 habitants, were independently shown to have lower energy consumptions per month when compared with a domestic electric shower generally used by a sample Brazilian family consisting of four members.

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