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Combined compact anaerobic reactors and lamella settlers for decentralized sewage treatment

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ABSTRACT

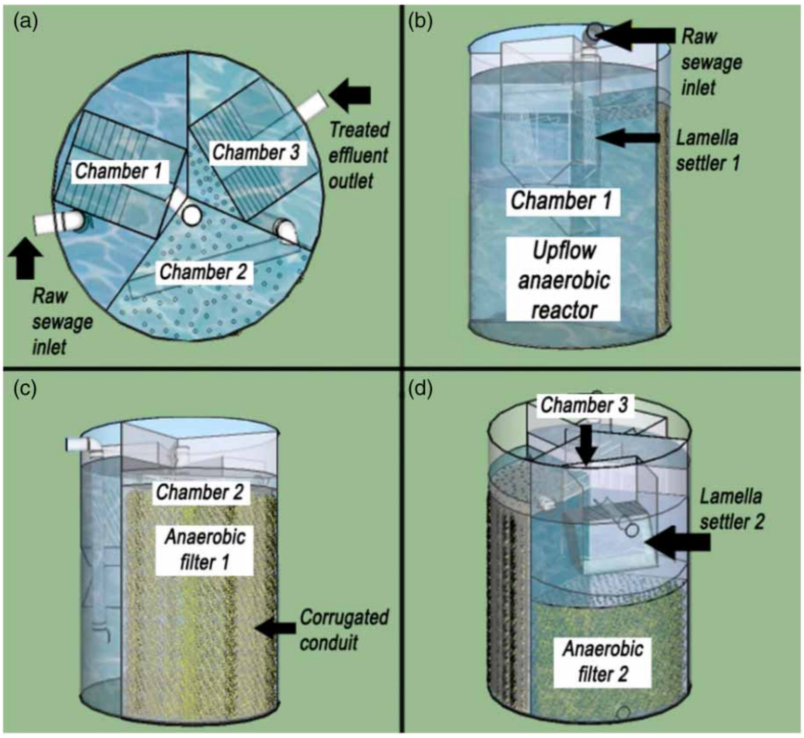
This work presents a compact plant's development and performance evaluation for the decentralized treatment of domestic sewage. The plant was conceived and installed in a house with four residents in Vicente Pires, Federal District, Brazil. Its purpose was to remove organic matter and solids using a low-cost biological treatment process that was simple to operate. The plant was essentially anaerobic, composed of an up-flow anaerobic reactor and an anaerobic filter, both associated with lamella settlers. It was operated under real conditions and monitored for nineteen months, with removal efficiencies (calculated over the medians) of 81% for COD, 83% for BOD, 51% for Total Solids, 55% for Total Volatile Solids, 87% for Total Suspended Solids, and 100% for Settleable Solids. The plant performed adequately, with no clogging between the plates of the lamella settlers, no offensive odours, and limited amounts of sludge and scum.

Key words: anaerobic filter, anaerobic sewage treatment, compact treatment plant, decentralized sewage treatment, household sewage, lamella settler

HIGHLIGHTS

- A compact sewage treatment plant was installed and monitored in a family house.
- Data from nineteen months of monitoring are presented.
- The work showed that anaerobic reactors can be combined with lamella settlers.
- Lamella settlers can be used to advantage to treat domestic sewage.
- Corrugated conduit chips can be used in anaerobic filters treating domestic sewage from a family house.

GRAPHICAL ABSTRACT



The compact sewage treatment plant (CSTP); (a) top view, (b) chamber 1, (c) chamber 2, (d) chamber 3.

INTRODUCTION

Intense population increase in cities is occurring, but the management capacity and financial resources are not available to serve these populations with conventional sanitation. Centralized sewage systems are very costly and their implementation is slow, making total sewage coverage in these urban environments unfeasible. Sanitation problems also exist in rural areas.

Several authors argue that the problem will be solved by decentralized sewage treatment systems (DEWATS), defined by the maximum sewage flow of 1,000 $m^3 \cdot d^{-1}$, either in individual dwellings or small collective systems (Ulrich *et al.* 2009). DEWATS must be of low cost and have little or no need for operation and maintenance, as well, usually working without external power input. DEWATS treat raw wastewater at or near its generation site (Bernal & Restrepo 2012).

According to Capodaglio *et al.* (2016, 2017), DEWATS offer several advantages. They can treat effectively and efficiently domestic sewage to protect health and water quality, support local water supplies since wastewater treated by decentralized systems is more likely to remain in the local watershed, make it easier for a community to implement local water reuse schemes for non-potable purposes by reducing demand for treated drinking water, and facilitate local energy production and resource recycling.

An individual, compact and modular sewage treatment system is advocated in this study that can be transported to installation sites after manufacture. Large-scale manufacturing of the system units can lower their production costs. On this basis, the units should be made of materials suitable for transport and to prevent soil and groundwater contamination.

Anaerobic reactors are well accepted for use in DEWATS. As they have no effective action on nutrients and pathogenic organisms, anaerobic reactors are commonly used in conjunction with other aerobic or anoxic biological processes and with filtration or disinfection processes.

Anaerobic filters (fixed-bed biological reactors) play an important role in DEWATS. They are relatively low-cost and compact, and produce small amounts of excess sludge. They are, therefore, suitable for decentralised sanitation. However, one of the greatest impediments to the widespread adoption of anaerobic filters is the cost of the packing media, which can be the same as reactor construction (Frankin 2001;

van Haandel *et al.* 2006). Heavy packing media require more reinforced and expensive reactor structures. Therefore, low-cost and low-density materials have been evaluated, including polyurethane foam, cut conduit rings, bamboo rings, ceramic bricks, loofah sponge, porous floating ceramic media, ground tire rubber, expanded clay, blast furnace cinders, activated charcoal, and coconut shells. In this study, corrugated conduit chips were used as a support medium, as they come from building construction waste and are very cheap.

A trend in DEWATS development has been to unite different processes in compact systems (Foresti *et al.* 2006). In this sense, Sousa & Chernicharo (2005) developed a new configuration of DEWATS incorporating the main advantages of septic tanks, such as ease of installation, operational simplicity, and efficient removal of solids and organic materials. They built four demonstration-scale prototypes, in a 1,750 L cylindrical tank, sub-divided into three compartments with serial flow. Prototypes 1 and 2 each had three compact chambers – a modified septic tank, a UASB reactor followed by anaerobic filter, and a percolating biological filter. In prototypes 3 and 4, the percolating biological filter was modified to a UASB reactor followed by anaerobic filter. All four configurations had the same volume, but the heights and areas were different, which enabled the use of different surface application rates. To simulate reality, feed was intermittent, like the flow of sanitary hardware. The units all showed high removal efficiencies and yielded final effluents with low concentrations of BOD, COD, and TSS, even when subjected to hydraulic load peaks. Prototypes 3 and 4 achieved the best results, removing efficiencies around 90% of COD, 88% of BOD, and 97% of TSS. This demonstrates the system's potential for treating household sewage of dispersed populations. This system's volume was equivalent to that of a septic tank, but its effluent's characteristics were similar to those of a septic tank combined with an anaerobic filter of approximately twice its volume.

Sousa *et al.* (2020) combined anaerobic pre-treatment and conventional aerobic technologies in a single compact unit, with the potential to provide practical, sustainable, low-cost, decentralized sewage treatment. The single-family plant consisted of a UASB reactor, an anaerobic up-flow bed filter, and an aerobic intermittent sand filter. The mean efficiencies were, respectively, 90, 93, and 75%, for Total COD, TSS and total Kjeldahl nitrogen, with hydraulic loading rate of 380 $L \cdot m^{-2} \cdot d^{-1}$ on the intermittent sand filter. The intermittent sand filter feed was achieved with a siphoning tank, which guaranteed the filter's automatic aerobiosis.

In this study, an initial sewage treatment module was tested. It comprised robust anaerobic biological treatment processes capable of withstanding sudden flow and quality of raw sewage variations, and receiving coarse solids without being compromised. The processes set can prepare the effluent to be treated later, if necessary, in subsequent modules so that the final effluent meets the environmental or water reuse criteria. This initial module consists of an up-flow anaerobic reactor with a lamella settler on top, functioning as a septic tank, Imhoff tank, and UASB reactor. After that, the effluent passes through an anaerobic filter that also discharges through another lamella settler.

Anaerobic sewage treatment has been tested and researched extensively, but few studies have monitored anaerobic treatment in individual sewage systems under real conditions over long periods. In this study, the period was long enough to include normal problems, such as travel by the house occupants that puts the system out of service, parties, and celebrations that increase the contribution of sewage substantially, and system cleaning to remove sludge and scum.

The search for sustainability in sewage treatment is supplied by anaerobic biological treatment, with the possibility of reusing water, using biogas for energy production, and using septic sludge in agriculture (Capodaglio *et al.* 2016, 2017).

Use of a set of anaerobic reactors and biological filters increases process security and stability, without requiring any routine operational procedure. Maintenance is reduced to annual removing of accumulated sludge. This can be done with a common vacuum pump on a septage truck, which takes it to a central treatment plant of some sort.

Lamella settlers have been used successfully in water treatment since the 1970s. However, there has been great resistance to their use in wastewater treatment, due to the perceived risk of the tubes or plates clogging – for example, through the formation of biofilm or the high suspended solids content commonly found in wastewater. The earliest research found into lamella settlers in wastewater treatment occurred in mid-2004, when they were used as an adjunct to anaerobic treatment (Sousa & Chernicharo 2005).

Silva & Nour (2005) studied a sewage treatment plant composed of an anaerobic/aerobic baffled reactor with four sequential chambers, the first three anaerobic and the fourth aerobic. The effluent went to a parallel plate lamella settler. The latter's polypropylene plates were 250 mm long, 2 mm thick, inclined at 60° to the horizontal, and 50 mm apart. System's performance was evaluated at different hydraulic retention times (HRT), and the best removal efficiencies for Total COD and TSS were 73.7% and 78.8%, respectively, at total 8-hour HRT (4 hours for each phase).

The objective of this work is to describe the compact sewage treatment plant and the monitoring results obtained from it over nineteen months. The plant incorporated only anaerobic biological processes, which do not remove pathogenic organisms and/or nutrients; the main purpose was to verify the plant's efficiency in removing organic matter and solids.

MATERIALS AND METHODS

The methodology used was basically the design, manufacture, installation, and operation of a compact sewage treatment plant (CSTP) comprising anaerobic reactors. The CSTP was installed in a single-family home and its operation in real conditions was monitored.

Family dwelling

The region where the CSTP was installed has no sewage collection network. The home had four inhabitants, and was in the Colônia Agrícola Samambaia, Vicente Pires, Federal District of Brazil, at 15° 49′ 07.4″ S, 48° 02′ 24.6″ W. The site's altitude is approximately 1,130 m. The climate in the Federal District is tropical seasonal, with hot and humid springs and summers and cool, dry autumns and winters. The average ambient temperature varies from 13 to 27 °C, constituting an annual average of around 20 °C.

The residence covers approximately 600 m^2, and has a kitchen, two bathrooms, a living room, a pantry, a green area, and a swimming pool. Household sewage was managed using a septic tank and soakaway system. The CSTP was installed replacing the septic tank discharging to the soakaway.

The residence was supplied by the public water supply system, but water from a well was used for the pool, green area irrigation, and washing external floors. Because of this, the sewage flow rate could be measured using the water supply system meter.

Compact sewage treatment plant (CSTP)

The system's design premises were: (1) efficiency; (2) lightness for transport; and (3) smallest possible volume. It should also not need electricity supply. The process selected was biological anaerobic, which is efficient in hot climates, easy to maintain and operate, and cheap and simple to install.

The system's design incorporated concepts of UASB reactors, anaerobic filters, and lamella settling. The CSTP was made of fiberglass. Figure 1 shows the details of the design of the CSTP.

The CSTP was designed for five inhabitants producing 160 L-sewage·inhab^{-1}·d^{-1} and annual sludge disposal. The dimensions are given in Table 1.

The CSTP, as a whole, is cylindrical because it occupies the least area for installation and has the fewest dead zones. It is divided into three chambers:

- **Chamber 1:** This is an adaptation of an Imhoff tank, with raw domestic sewage entering through the bottom. It is an anaerobic biological reactor with a suspended medium and upward flow, and occupies 40% of the cylinder, its top has a lamella sedimentation compartment with nine plates tilted at 60° to the horizontal and spaced 5.0 cm apart, as per Silva & Nour (2005). The upper compartment has deflector plates that prevent scum from entering and work as a three-phase separator (solids, liquid, and gas). The chamber's design HRT was 1.57 days.
- **Chamber 2:** This is an ascending anaerobic filter and occupies 30% of the cylinder. The filter medium comprises pieces of corrugated conduit, 32 mm in diameter and in pieces 30 mm long, following Sousa & Chernicharo (2005) and Chernicharo & Sousa (2013). According to Chernicharo (2007a, 2007b), the material's porosity is around 95%, its specific surface is about 200 $m^2 \cdot m^{-3}$, and it weighs 55 $Kg \cdot m^{-3}$. A perforated plate was installed near the top of the chamber to prevent passage of the conduit filling to the next treatment stage. The chamber's design HRT was 0.88 days.
- **Chamber 3:** This chamber also occupies 30% of the total volume of the cylinder volume and it is a second anaerobic filter followed by a secondary lamellar decanter. In its lower part is an ascending anaerobic filter, also containing the same corrugated conduit used in chamber 2. In the upper part, another lamellar decanter with parallel plates was installed. It has ten plates tilted at 60° to the horizontal and 3.0 cm apart (as the liquid has a lower suspended solids content. The chamber's design HRT was 0.90 d.

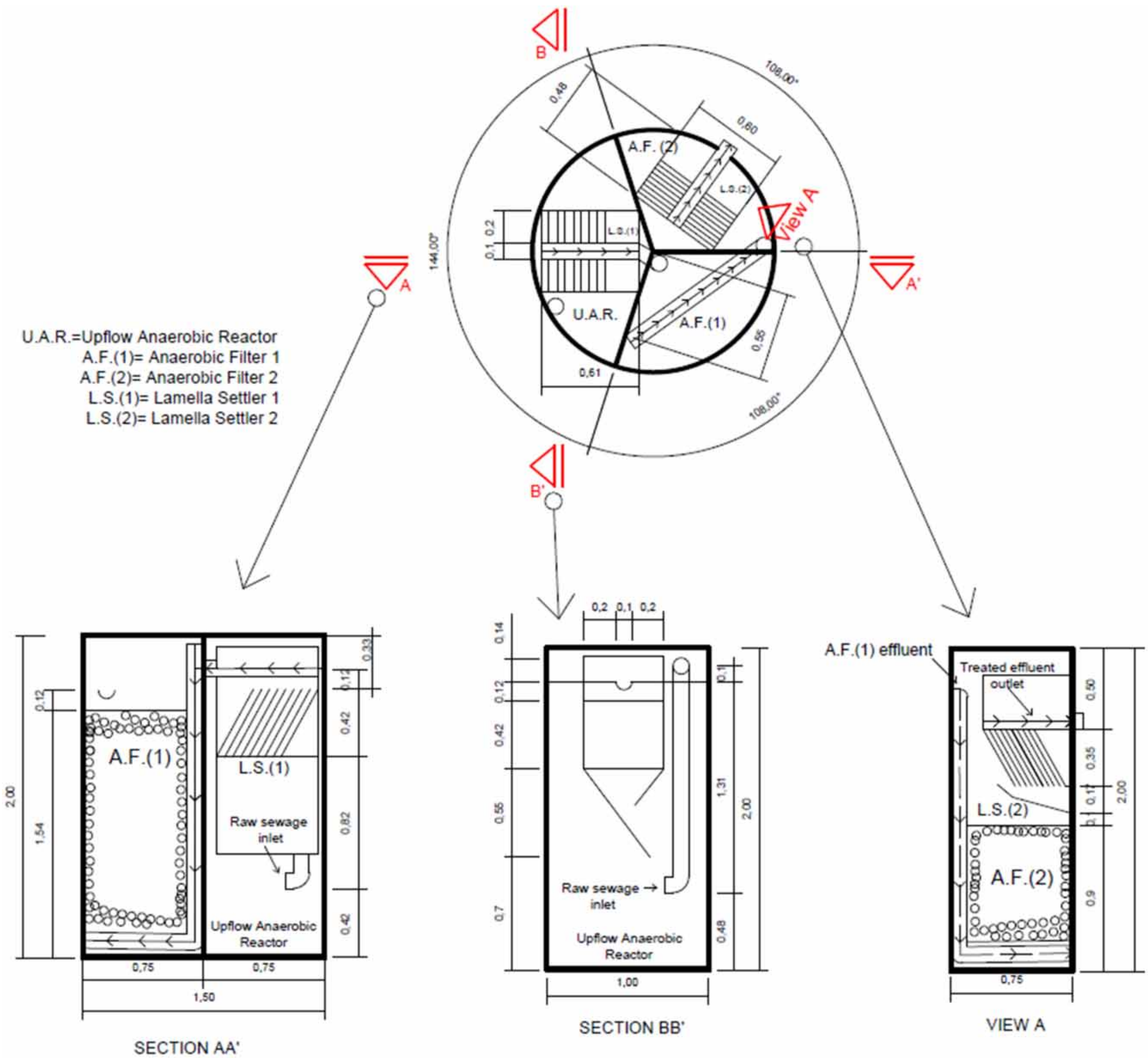


Figure 1 | CSTP design details.

Table 1 | CSTP dimensions

Entire treatment plant				**Chamber 1**		**Chamber 2**		**Chamber 3**	
V (m^3)	**A (m^2)**	**H (m)**	**D (m)**	**V (m^3)**	**A (m^2)**	**V (m^3)**	**A (m^2)**	**V (m^3)**	**A (m^2)**
3.53	1.77	2.00	1.5	1.41	0.71	1.06	0.53	1.06	0.53

V, volume; A, surface area; H, working height; D, diameter.

While the full CSTP design HRT was 3.35 d, the actual operational HRT was much higher.

Raw domestic sewage is fed to the system by a pipe that leads it to the bottom of chamber 1. At the top, the lamellar settler's deflector plates separate the foam, and allow the effluent to enter the settler. The clarified effluent from the settler is passed to the bottom of chamber 2, where it continues its upward flow. After passing through the first anaerobic filter, it is collected at the top and is transferred to the bottom of chamber 3, from where it continues again in its upward flow through the second anaerobic filter. A perforated plate in chamber 3 prevents pieces of conduit moving to the next phase, while a deflector plate prevents foam from passing to the system outlet. Immediately after the deflector plate, the effluent moves through the second laminar settler, from where it is discharged.

The CSTP was manufactured entirely in fiberglass. The spray-gun rolling process (spray-up) was used for moulded parts, and manual layering (hand lay-up) to assemble the internal parts.

CSTP operation, monitoring and follow-up

Inoculation was carried out following procedures described by others, for example, Pereira-Ramirez *et al.* (2001) and Aisse & Sobrinho (2001). The sludge used as inoculum came from a septic tank that had not been cleaned for a year. About 10% of each chamber's working volume was filled with sludge – a total of 270 litres – comprising 110 litres in chamber 1 and 80 litres each in chambers 1 and 2.

Four sampling points were used in the CSTP: A – raw sewage inlet, chamber 1; B – discharge from chamber 1; C – discharge from chamber 2; and D – discharge of final effluent from chamber 3.

Various quality characteristics were analysed twice weekly. Temperature, pH and conductivity were measured *in situ*. Alkalinity, COD, BOD, nitrite, nitrate, total phosphorus, total solids (TS), total volatile solids (TVS), total suspended solids (TSS), and settleable solids (SetS) were determined in the laboratory. The samples were collected and examined according to the procedures described in the Standard Methods for the Examination of Water and Wastewater (APHA 2017).

It proved difficult to install sewage flow meters at the site, so estimates were made based on the daily water consumption by the residence while the CSTP was in operation, using the residential water meter. The average sewage flow was determined as 85% of water consumption, after taking several factors into account.

RESULTS AND DISCUSSION

Table 2 shows the physical-chemical characterization of the samples and the removal efficiency at various sampling points. The data were analysed using descriptive statistics with measures of central tendency and data dispersion. The data include the system stabilization phase (two months) and the CSTP was cleaned in month 12, the central tendency measure that best represents the characterization data is the median, which is not affected by extreme values.

As the CSTP was installed *in situ*, some raw sewage characteristics differ from those found in sewage from conventional sewage networks. The raw sewage entering the CSTP was more concentrated than most sewage discussed in the literature. The mean BOD of the raw sewage – 730 mg·L^{-1} – exceeded that presented by several authors. The COD of the raw sewage entering the CSTP was also high, with a mean of 1,339 mg·L^{-1}.

The temperature of the sewage in the CSTP remained practically constant. The median of the influent was 23.5 °C, at the exit of Chamber 1 and Chamber 2 it was, respectively 23.8 °C and 23.6 °C, and at the plant exit, it was 23.5 °C. Sample collections were performed early in the morning, when the temperature is relatively low. Anaerobic sludge blanket reactors perform well if the sewage temperature is above 20 °C, but their performance is compromised with temperatures below 16 °C (Chernicharo 2007a, 2007b). Thus, the temperatures at the four sampling points were considered satisfactory for maintaining the microbial activities in the plant.

Some 50% of the pH results for the household sewage were between 6.55 and 6.90 (median 6.70). The median pH of the treated effluent was 6.83, with 50% of the data concentrated between 6.69 and 6.98, while intermediate collection points B and C reported medians of 6.77 and 6.84, respectively.

The median total alkalinity concentrations were 300, 280, 296, and 295 mg-$CaCO_3$·L^{-1}, at the four sampling points, respectively, showing that the sewage passing through the CSTP has high buffering capacity. Thus, maintaining the pH close to neutral might be associated with high alkalinity concentrations in the sewage.

The median COD concentrations at the four collection points were 1,356, 834, 429, and 254 mg·L^{-1}, respectively (means values 1,339, 828, 466, and 309 mg·L^{-1}), and the CSTP's median COD removal efficiency was 81% (mean 71%). For BOD the figures were 697, 468, 183, and 122 mg·L^{-1} (mean values 730, 463, 225, and 152 mg·L^{-1}), at the sampling points, with median BOD removal efficiency of 83% (mean 79%) for the CSTP.

The median COD/BOD ratio in raw sewage was 1.94. At the exit from chambers 1, 2 and 3 – the latter being the treated effluent – it was 1.78, 2.34, and 2.08, respectively. All of these values indicate that the raw sewage has a high biodegradable fraction, and the possibility of further biological treatment.

The COD and BOD results were also analysed by monitoring quarter – see Figure 2.

The median COD value varies irregularly at the four sampling points, with minor variation in the CSTP's final effluent. COD removal was significant throughout the trial. The median BOD concentration in the influent increased during the study, but fell at the other sampling points – that is, removal by anaerobic treatment improved over time, working better with higher organic loads. Large proportions of COD and BOD were

Table 2 | Sample characterisation and CSTP efficiency data

Sampling points and statistical parameters		pH	Alkalinity ($mgCaCO_3 \cdot L^{-1}$)	COD ($mg \cdot L^{-1}$)	BOD ($mg \cdot L^{-1}$)	Nitrite ($mg \cdot L^{-1}$)	Nitrate ($mg \cdot L^{-1}$)	Total phosphorus ($mgP \cdot L^{-1}$)	TS ($mg \cdot L^{-1}$)	TVS ($mg \cdot L^{-1}$)	TSS ($mg \cdot L^{-1}$)	SetS ($mL \cdot L^{-1}$)
Raw sewage influent (Point A)	**N[a]**	**96**	**96**	**83**	**59**	**75**	**76**	**76**	**95**	**95**	**93**	**97**
	Min NO[b]	6.05	150	564	422	0.02	4	30	210	136	31	1
	Max NO[c]	7.30	470	1,546	1,032	0.15	68	70	1,672	805	640	50
	Mean	6.72	315	1,339	730	0.10	24	45	1,216	724	362	23
	Quartile (75%)	6.90	350	1,452	835	0.11	38	51	1,133	539	368	25
	Median	6.70	300	1,356	697	0.08	17	44	787	421	243	8
	Quartile (25%)	6.55	270	1,168	647	0.06	10	38	657	339	184	3
	SD[d]	0.26	80	467	170	0.10	16	14	1,480	1,134	522	45
	CV (%)[e]	4	26	35	23	96	69	32	122	157	144	198
Final effluent (Point D)	**N[a]**	**96**	**96**	**96**	**58**	**75**	**69**	**75**	**94**	**94**	**93**	**97**
	Min NO[b]	6.30	180	154	9	0.02	0	24.0	205	33	10	0.0
	Max NO[c]	7.41	417	345	161	0.13	41	47	537	408	70	0
	Mean	6.86	296	309	152	0.07	12	36	420	217	34	0
	Quartile (75%)	6.98	335	343	149	0.09	22	40	438	259	44	0
	Median	6.83	295	254	122	0.07	6	36	389	189	32	0
	Quartile (25%)	6.69	272	222	86	0.05	2	32	330	158	20	0
	SD[d]	0.26	62	153	102	0.05	13	12	229	184	16	0
	CV (%)[e]	4	21	50	67	63	104	33	55	85	48	-
Removal efficiency (%)		**–**	**–**	**81**	**83**	**13**	**64**	**18**	**51**	**55**	**87**	**100**
Exit from chamber 1 (Point B)	**N[a]**	**96**	**96**	**96**	**58**	**74**	**75**	**77**	**95**	**92**	**95**	**97**
	Min NO[b]	6.30	180	435	326	0.01	0.0	20.6	359	70	10	0.0
	Max NO[c]	7.26	365	958	661	0.14	46	52	714	504	240	2.1
	Mean	6.77	272	828	463	0.09	16	38	573	279	110	1.0
	Quartile (75%)	6.91	300	926	542	0.10	31	42	592	354	157	1.0
	Median	6.77	280	834	468	0.08	8	38	531	259	131	0.3
	Quartile (25%)	6.61	247	761	435	0.06	5	32	476	212	56	0.1
	SD[d]	0.27	59	190	125	0.06	14	12	363	87	60	1.5
	CV (%)[e]	4	22	23	27	71	93	32	63	31	54	154
Exit from chamber 2 (Point C)	**N[a]**	**96**	**96**	**96**	**59**	**75**	**74**	**77**	**95**	**94**	**95**	**97**
	Min NO[b]	6.85	232	220	69	0.01	0.0	28	260	55	8	0.0

(*Continued.*)

Table 2 | Continued

Sampling points and statistical parameters	pH	Alkalinity (mgCaCO$_3$·L^{-1})	COD (mg·L^{-1})	BOD (mg·L^{-1})	Nitrite (mg·L^{-1})	Nitrate (mg·L^{-1})	Total phosphorus (mgP·L^{-1})	TS (mg·L^{-1})	TVS (mg·L^{-1})	TSS (mg·L^{-1})	SetS (mL·L^{-1})
Max NO[c]	7.26	368	666	477	0.14	42	45	671	391	199	1.0
Mean	6.85	292	466	225	0.08	14	37	485	235	79	0.7
Quartile (75%)	6.94	317	544	279	0.09	23	40	525	297	107	0.5
Median	6.84	296	429	183	0.07	7	37	467	218	78	0.2
Quartile (25%)	6.72	280	341	136	0.06	3	35	406	199	40	0.0
SD[d]	0.22	59	185	126	0.05	14	9	139	115	48	1.5
CV (%)[e]	3	20	40	56	64	100	24	29	49	61	215

[a]N, data number; [b]Min NO, minimum excluding outliers; [c]Max NO, maximum excluding outliers; [d]SD, Standard Deviation; [e]CV, coefficient of variation.

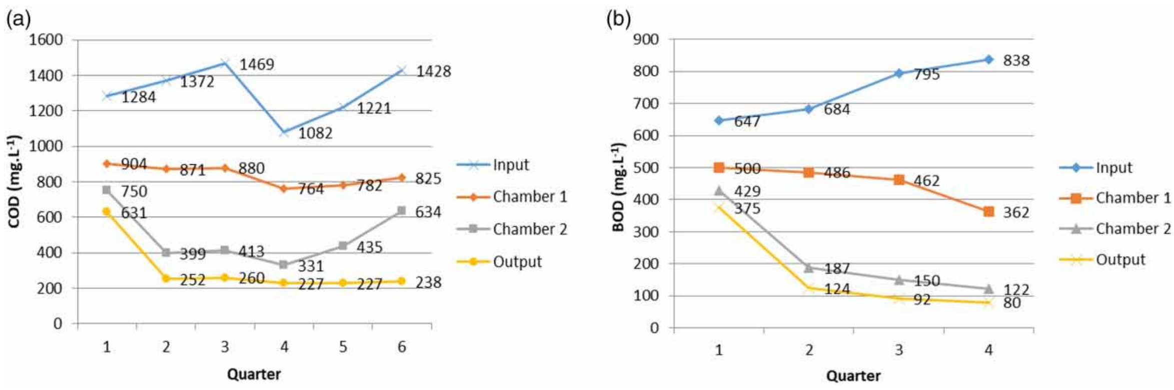


Figure 2 | Quarterly monitoring – median concentrations of (a) COD and (b) BOD.

removed in the first anaerobic filter (Chamber 2), but the second anaerobic filter and lamella settler (Chamber 3 and outlet) removed some more.

The median nitrite concentrations were 0.08 mg-N·L^{-1} in the influent and at Chamber 1's outlet, and 0.07 mg-N·L^{-1} in the effluents from both chambers 2 and 3. The CSTP's nitrite removal efficiency was 13% (low nitrite and other nutrients removal levels are expected from anaerobic biological treatment technology). Another module based on aerobic biological treatment would be required, added to the initial anaerobic module, for significant nutrient removal.

Median nitrate concentrations in sewage are usually very low (Von Sperling & Chernicharo 2005; Von Sperling 2007). However, the results found in the samples collected in the CSTP were relatively higher. It is possible that this is related to rapid ammonia nitrification. The median nitrate concentrations were 17, 8, 7, and 6 mg-N·L^{-1}, at the sampling points, and the median nitrate removal efficiency was 64%.

The median total phosphorus concentrations were also above those reported in the literature for sanitary sewage; that is, around 7 mg-P·L^{-1} (Von Sperling & Chernicharo 2005; Von Sperling 2007). The CSTP removed only 13% of total phosphorus, with median concentrations in the influent and treated effluent of 44 and 36 mg-P·L^{-1}, respectively.

The CSTP's median efficiency was 51% for TS and 55% for TVS. The highest solids removal efficiencies achieved were 87% for TSS, and 100% for SetS. The first lamella settler (chamber 1) removed approximately 96% of SetS. The second lamella settler (chamber 3) reached 100% efficiency.

The quarterly median SS and SetS removal are shown in Figure 3.

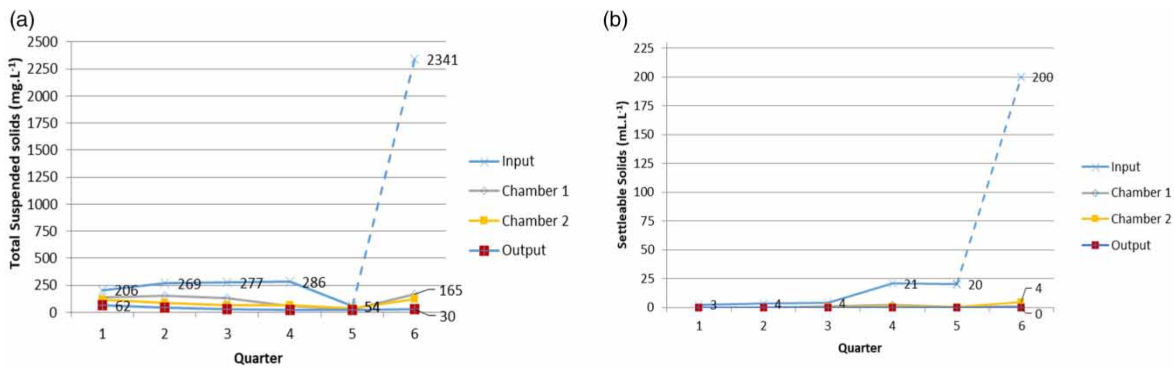


Figure 3 | Quarterly monitoring – median concentration of (a) TSS and (b) SetS.

In the sixth quarter of monitoring - Figure 3 - there was a sudden increase in the median concentration of both TSS and SetS in the influent sewage. It is thought that this might have occurred due to the replacement of the sampling equipment, the new sampler perhaps interfering with the sampling. Despite this, the CSTP's removal efficiencies remained above 80 and 100% for TSS and SetS, respectively.

The results obtained show that the CSTP met the recommendations for temperature, pH, BOD, and SetS Brazilian standards for the discharge of sanitary effluents – Resolution No. 430/2011 National Council for the Environment – CONAMA). The recommendations are that the temperature should remain below 40 °C, pH should be in the range between 5 and 9, SetS should be below 1 $mL \cdot L^{-1}$, and minimum BOD removal should be 60%

The BOD and COD removal efficiency results achieved by the CSTP's chambers were analysed across operating phases: (1) start-up or stabilization, (2) stable, and (3) post-stability.

Table 3 shows the mean BOD removal efficiency of the CSTP and each of its chambers, during the operating phases. The mean total BOD removal efficiency achieved was 45% in the first phase, 85% in the second, and 88% in the third.

Table 3 | Mean BOD concentrations and removal efficiency of the whole plant and each constituent chamber across the three operating phases

Data type	Raw sewage ($mg \cdot L^{-1}$)	Chamber 1 Effluent ($mg \cdot L^{-1}$)	Chamber 1 Efficiency (%)	Chamber 2 Effluent ($mg \cdot L^{-1}$)	Chamber 2 Efficiency (%)	Chamber 3 Effluent ($mg \cdot L^{-1}$)	Chamber 3 Efficiency (%)	Sewage treatment plant (total) Efficiency (%)
Phase 1 - start-up								
N[a]	12	11		11		11		
Mean	632	505	20	434	14	349	19	45
Phase 2 - stable								
N[a]	32	32		32		32		
Mean	733	491	33	183	63	112	39	85
Phase 3 - post-stability								
N[a]	15	14		15		14		
Mean	775	389	50	167	57	93	44	88

[a]N, data number.

Table 4 shows the CSTP's COD removal efficiency as a whole and in each chamber.

Table 4 | Mean COD concentration and removal efficiency of the whole plant and each constituent chamber across the three operating phases

Data type	Raw sewage ($mg \cdot L^{-1}$)	Chamber 1 Effluent ($mg \cdot L^{-1}$)	Chamber 1 Efficiency (%)	Chamber 2 Effluent ($mg \cdot L^{-1}$)	Chamber 2 Efficiency (%)	Chamber 3 Effluent ($mg \cdot L^{-1}$)	Chamber 3 Efficiency (%)	Sewage treatment plant (total) Efficiency (%)
Phase 1 - start-up								
N[a]	12	11		11		11		
Mean	1,280	892	30	768	14	650	15	49
Phase 2 - stable								
N[a]	32	32		32		32		
Mean	1,407	920	34	422	54	265	37	81
Phase 3 - post-stability								
N[a]	39	53		53		53		
Mean	1,197	737	38	419	43	258	38	78

[a]N, data number.

The CSTP efficiencies were lower when reported as means than as median values. Its median efficiencies were 81, 83, and 87% respectively for COD, BOD, and TSS. The mean removal efficiencies for the same parameters were 77, 79 and 90%. The mean TSS removal was slightly higher than the median value.

Since most sewage treatment plants' efficiency results are based on means, it is these that should be used for comparison with the results from others. The closest concept found in the DEWATS literature was that of Sousa & Chernicharo (2005). Their prototypes 1 and 2 showed mean COD, BOD and TSS removal efficiencies of 77, 70, and 85%, respectively, slightly lower than the results in this study. The studies differ in that Sousa & Chernicharo (2005) worked with municipal sewage adapted to the hydraulic conditions of variable flow, trying to simulate DEWATS flow rates in a controlled system, without cleaning or stops, and fed with less concentrated raw sewage. The plant's HRT that they adopted (1.0 day) was much lower than the CSTP's HRT (3.35 days).

The efficiency results obtained in this study are compatible with those reported for systems comprising septic tanks and anaerobic filters, which are in the range of 70–80% for COD, 80–85% for BOD, and 40–86% for TSS (Von Sperling 2007; Lourenço & Nunes 2020).

The CSTP size was chosen on the basis that it was to be cleaned annually. This period proved adequate, as no problems arose during the 19 months of operation.

While the CSTP was in operation, the amount of waste (sludge and scum) was verified and quantified. Approximately 0.058 m^3 of scum was removed seven months after start-up, and the annual scum production was recorded as approximately 0.1 m^3. Pereira *et al.* (2019), working with conventional sewage being treated in UASB reactors, recorded 21 $mL \cdot (kgCOD_{applied})^{-1}$ scum production. Likewise, Rosa *et al.* (2017) obtained values between 6.8 to 14.6 $mL \cdot (kgCOD_{applied})^{-1}$, and Santos (2014) found scum production between 6.79 and 10.33 $mL \cdot (kgCOD_{applied})^{-1}$. The CSTP scum production was 395 $mL \cdot (kgCOD_{applied})^{-1}$, about 20–40 times higher than the recorded yield from UASB reactors. Several factors determine the amount of scum produced, but one of the explanations for this difference might be that preliminary treatment takes place within the plant in this study, while UASB reactors require separate efficient preliminary treatment before the sewage enters the lower compartment. It is also true that, when cleaning the reactor surface, it is very difficult to separate the scum from the surrounding liquid, and that much of that liquid may have been measured as scum.

14 months after the startup, all CSTP's chambers were cleaned for the first time, using a vacuum cleaner truck. The liquid removed – the septage – was a mixture of scum, liquid from the tank, and sludge. The septage volume removed from the CSTP corresponded to the total working volume that is contained in the plant. Thus, some 3.53 m^3 of septage would be produced annually, equivalent to 2.42 $L \cdot inhab^{-1} \cdot d^{-1}$. This is considered high, as the Brazilian Standard for septic tanks establishes a maximum septage production of 1.0 $L \cdot inhab^{-1} \cdot d^{-1}$ (ABNT 1993). This is explained by the higher HRT of the CSTP. However, it is still within the wet sludge production range found by Von Sperling (2007) for sewage treatment systems comprising a septic tank and anaerobic filter (between 0.5 and 2.8 $L \cdot inhab^{-1} \cdot d^{-1}$).

The sludge quantification is more accurate when done by calculating the total amount of suspended solids inside the tank when it was cleaned – that is, TSS multiplied by the tank's working volume. Table 5 shows the estimated amount of dry sludge produced after 19 months.

Table 5 | Estimate dry sludge production by the CSTP

Number of chambers	Working volume (m^3)	Mean TSS in chamber ($kg \cdot m^{-3}$)	Sludge produced after 19 months (kg)
1	1.41	188	265
2	1.06	156	165
3	1.06	126	133
Total	3.53	–	563

The annual sludge production equivalent of 563 kg (in 19 months) is 375 kg, which equates to 0.243 $kg\text{-}TSS \cdot inhab^{-1} \cdot d^{-1}$. This is around six to nine times higher than that Von Sperling (2007) derived from data from several other authors (between 0.027 and 0.039 $kg\text{-}TSS \cdot inhab^{-1} \cdot d^{-1}$).

Although the CST's cover was kept open, there were no odour problems. This was confirmed by regular consultations with local residents and neighbours.

Gas collection equipment could not be installed in the CSTP, but gas yield should not exceed the values recorded by Souza *et al.* (2012) in UASB reactor settler chambers (range from 0.21 to 0.37 $g\text{-}S \cdot m^{-2} \cdot d^{-1}$ and from 11.0 to 17.8 $g\text{-}CH_4 \cdot m^{-2} \cdot d^{-1}$). Lourenço & Nunes (2020) found that the methane emission rate from septic tanks is in the range of 11–27 g·inhab^{-1}·d^{-1}, indicating that methane production by the CSTP would be around 100 g-CH_4· d^{-1}.

Using the methodology described above, the average water consumption of 0.601 m^3·d^{-1}suggests that the average sewage flow was 0.511 m^3·d^{-1} (0.128 m^3·d^{-1}·inhab^{-1}). On this basis, the CSTP HRT was 6.9 days, which is considered very high. According to Chernicharo (2007a, 2007b), anaerobic filter HRT varies between 4 and 10 hours and UASB reactor HRTs are between 8 and 10 hours. The entire CSTP should, therefore, have a maximum HRT of 20 hours (0.8 days), which shows that the size of the module could be reduced significantly.

CONCLUSIONS

The raw sewage from the house where the compact sewage treatment plant was installed contained mean concentrations of 1,339 and 730 mg·L^{-1} of COD and BOD, respectively (medians of 1,356 and 697 mg·L^{-1} of COD and BOD, respectively).

The compact plant, working under real conditions, was efficient in removing organic matter and solids, and met the Brazilian Standards for wastewater discharge. Another module would be required to raise the effluent quality to that needed for some form of water reuse.

The lamella settlers, particularly that in the first chamber, were efficient. Neither became clogged at any time. This proposed arrangement becomes a satisfactory alternative in the decentralised treatment of domestic sewage.

The high operating HRTs in the project and the removal efficiencies achieved indicate that smaller plants could operate successfully and meet the discharge criteria.

The corrugated conduit chips used as filter medium are cheap and light, and proved acceptable.

The one year period between cleaning the plant proved adequate. The quantities of scum, sludge, and septage were reasonable, could be managed at low cost, and did not impair plant operation or efficiency.

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DATA AVAILABILITY STATEMENT

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

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