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TREATMENT OF SEPTIC TANK SLUDGE IN A VERTICAL FLOW CONSTRUCTED WETLAND SYSTEM

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ABSTRACT: The study consisted of the evaluation of the treatment of septic tank sludge in a vertical constructed wetland system (CW), built according to the first stage of the French system. The system operated also for sewage treatment and one of the beds (area of 29.1 m², height of the support medium of 0.7 m and planted with Tifton 85 grass, *Cynodon dactylon Pers*), began to receive the application of sludge from clean-pit trucks once a week. The percolated liquid was directed to post-treatment in the other two beds of the French system. The application of the raw sludge had average hydraulic loading rate of 13.1 m³/m².year and solids loading rate of 81 kgTS/ m².year. The system improved the quality of percolated liquid in terms of carbonaceous and nitrogenous matter (average COD removal efficiencies of 82% and TKN of 63%), but the percolate post-treatment strategy did not result in substantial improvements. The dewatering of the accumulated sludge on top of the bed occurred satisfactorily (55% of dry solids), the Tifton 85 grass was resistant to the operational conditions and the system proved to be a compact technology (sludge treatment capacity of an equivalent population between 1140 and 3799 inhabitants in the unit of 29.1 m^2, corresponding to 39 to 131 inhabitants per m^2 of surface area).

KEYWORDS: constructed wetlands, septic tank, post-treatment, sludge.

INTRODUCTION

Sewage collection and treatment are still a challenge in the world. Individual treatment systems such as septic tanks can be an alternative to properly dispose domestic effluents. Sewerage from 2.7 billion people around the world occurs through local technologies, such as septic tanks, and this number is expected to grow to 5 billion by 2030 (Strande et al., 2014). The septic tanks stand out because of some advantageous characteristics, such as on-site treatment, relatively low cost and operational simplicity. However, maintenance needs to be periodic, since the sludge accumulated in the tank must be removed, which occurs through the services of companies known as “plungers” or “clean-pit trucks”, some of which are not environmentally regulated and do not provide appropriate disposal of the collected material.

Inadequate methods of sludge disposal can lead to contamination of water bodies and pose a risk to the environment and public health (Jong & Tang, 2014). This sludge shows high concentrations of organic matter, nitrogen and solids forms, which are not typical of sludge from sewage treatment plants (STP), or sewage. In addition, clean-pit trucks do not always collect only sludge from septic tanks, but also, for example, grease trap residues or chemical toilets effluents, leading them to be even more heterogeneous and difficult to characterize. Nevertheless, in order to standardize the nomenclature, all the material collected by the clean-pit trucks will be mentioned in the text as septic tank sludge.

For Bassan et al. (2013), management of septic tank sludge is a challenging problem in low-income countries, where much of the urban population depends on local treatment systems. In some countries of Europe, Asia and Africa (Uggetti et al., 2010), a technological alternative for anaerobic sludge, including septic tanks, has been the treatment by constructed wetland systems (CW). In this case, the most suitable CW variant for the treatment of septic tank sludge is of the vertical flow. However, the percolate, after a single passage through the bed, may still contain high concentrations

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of the main constituents, such as organic and nitrogenous matter. Therefore, one possibility of improving its quality would be the use of percolate recirculation on the same unit or post treatment in a second vertical flow unit.

The circulation of percolated liquid, especially with regard to the joint treatment with sewage sludge, is a subject that has not yet been researched. Foladori et al. (2013) state that, despite the increasing interest of the CW with recirculation and/or aeration, this topic has not yet been extensively investigated, with most applications being at laboratory-scale. The configurations of CW with recirculation or post-treatment have presented some variants, such as: the use of hybrid systems (horizontal CW and vertical CW), in which, after percolating by the two units, the final effluent returns (recirculates) to the first stage; the recirculation of only a fraction of the effluent; the performance of more than one recirculation; the use of the same bed for the application of the influent and for the recirculation of the effluent; the occurrence of the application in one bed and the post-treatment in another; among others (Prost-Boucle & Molle, 2012).

The French system (Cemagref/Irstea) of vertical CW has been widely used in some countries for the treatment of domestic sewage. A possible simplification, in tropical and developing regions, would be the implementation of only the first stage of the French system, composed of three beds in parallel. The main motivation and the differential of this research were to have an extension of the scope of the French system, studying the possibility of having, with the three beds, one unit dedicated to the septic tank sludge and the other two units dedicated to the sewage treatment and post-treatment of the percolate from the sludge unit. Also noteworthy is the low availability of data for Brazil about the treatment of septic tank sludge in CW in full scale, and the lack of data with the present configuration.

Therefore, the aim of this study was to evaluate the performance of a vertical-flow CW (first stage of the French system) with gravel beds and Tifton-85 grass (*Cynodon dactylon Pers*) in the treatment of septic tank sludge, including post-treatment of percolated liquid. This study also covers the study of Calderón-Vallejo et al. (2015).

MATERIAL AND METHODS

Description of the treatment system

The research was carried out at the Center for Research and Training in Sanitation (CePTS), of the Federal University of Minas Gerais (UFMG) and the Minas Gerais Water and Sanitation Company (COPASA), located at *Arrudas* STP in Belo Horizonte, Brazil, with geographical coordinates: latitude 19°53’42”S and longitude 43º52’42”W. The climate of the region according to the classification of Köppen is of the Cwa type - tropical of altitude, with a dry period that extends from April to September and a rainy one that goes from October to March. The average air temperature was 21°C.

The CW was built in 2007, with typical characteristics of the first stage of a French vertical flow system (three parallel units, with pulse feed alternating between the beds), and the project was initially designed for the treatment of sewage only. In 2013, the system was modified, still consisting of three vertical filters, with only one bed receiving the raw sludge application from the clean-pit truck and was identified as the Sludge Unit (SU). The other two beds were fed by sewage (population equivalent of 100 inhabitants), operating in parallel and alternately, with periods of feeding and rest, of one week each. These two beds also received the percolated liquid from the SU during the rest of the operational cycle, being denominated as Percolate Units (SU). The raw sludge was applied to the sludge unit as a pulse, flowing vertically through the bed, and exiting the bottom drain without retention within the filtering layer. Therefore, after the application the medium was not saturated, with air occupying the empty spaces and allowing the occurrence of aerobic conditions. The percolate from the sludge unit was directed to one of the two post-treatment units and, as the application was in the bed that was at rest, the percolate was not mixed with the sewage. Each one of the three beds is 3.1 m wide, 9.4 m length and 1.0 m of sidewall, filled with 0.70 m of support medium (Figure 1), comprised of 0.40 m of gravel 0 (2.4-12.5 mm) in the top layer, 0.15 m of gravel 1 (4.8-25 mm) in the middle layer and 0.15 m of gravel 3 (19-50 mm) in the lower layer, and planted with Tifton 85 grass (*Cynodon dactylon Pers*). In this case, the area of each bed was 29.1 m² and the total area of the system was 87.4 m². At the bottom of each unit was the drainage system (collection of the percolate) and also of ventilation, through perforated tubing, with openings at each end, above the bed.

The granulometry used was designed for the treatment of sewage, without foreseeing, at the time, the use for the treatment of sludge. For the research, the original granulometry was maintained, without modifications for the reception of the sludge. In addition, the application of sewage in the percolate units was inserted in the context of another project and was not the object of research of this study.

The operation of the sludge system started in September/2013 and lasted until November/2014 (405 days). Once a week the sludge from a clean-pit truck from different companies was applied, with a volume of approximately 8.0 m³. Figure 1 shows the system schematics and its overview.

In order to reproduce the full-scale operating conditions, the solids loading rate was not controlled at each application, as happens in other literature studies, and was only determined after the analysis of the total solids concentration in the laboratory. In relation to the hydraulic loading rate, the beds received all the volume transported by each truck, also implying different rates for each batch. This strategy was adopted, because in a real locality, possibly, these would be the conditions of operation, without absolute control on the volumes and loads applied.

In addition to the described full-scale treatment system, pilot-scale tests were conducted to evaluate the effect of percolate recirculation. The pilot CW consisted of two PVC columns with the same characteristics of the system already described, altering only the scale (diameter of 0.150 m, with area of 0.0165 m²) and adding the recirculation strategy, in which the percolated liquid of the unit of sludge was recirculated to the same unit (unlike the actual scale, where the percolate was post-treated in another unit).

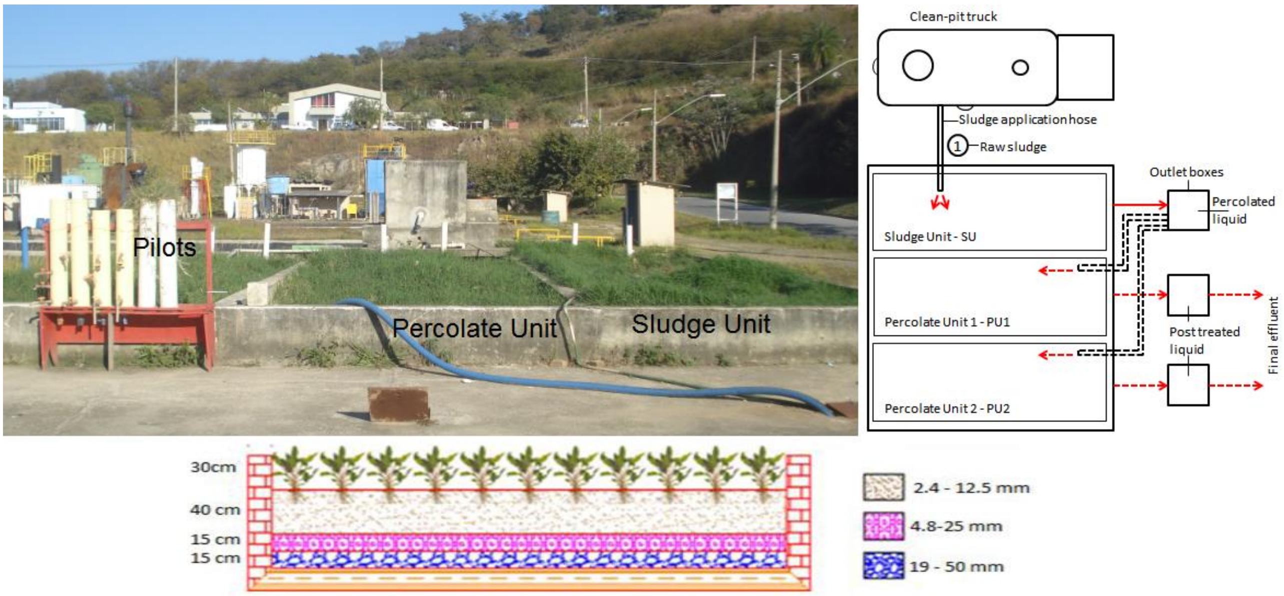

FIGURE 1. Overview, cross section and schematics of the CW system built for the septic tank sludge treatment.

Analyzed parameters and statistics

In order to verify the performance of the system, the following parameters were weekly evaluated: Dissolved Oxygen (DO), Hydrogenionic Potential (pH), Temperature, Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Kjeldahl Nitrogen (TKN) Ammonium ion ($N\text{-}NH_4^+$), Total Solids (TS), Total volatile solids (TVS), *Escherichia coli* (*E. coli*) and Total Coliforms (TC). Subsequently, after 405 days of operation, the non-parametric Mann-Whitney U test, with a significance level of 5% ($\alpha = 0.05$), was applied for comparisons of the results obtained with the raw sludge, percolated liquid and post-treated liquid samples with the aid of the Statistica 8.0 program. During this monitoring period, the number of monitoring data for each parameter was around 30 to 40.

The monitoring points consisted of the raw sludge, the percolate from the sludge unit and the effluent from the percolate post-treatment unit. The samples collected in the effluent from the two post-treatment units concern only the percolate, since there was no sewage at the moment of application, because the unit was in the rest stage of the operational cycle.

Monitoring of sludge accumulated at the top of the sludge bed

Sampling of the accumulated sludge layer in the SU bed occurred every 14 days, approximately. For the samples collection, PVC pipes were used, which were inserted in the sludge layer from the bed, removing that portion of accumulated sludge, which resembled a compacted soil. This portion of the accumulated sludge in the bed was sent to analyze the percentage of total solids and humidity in the laboratory. As the bed has a length:width ratio of 3:1, the samples were collected at three distinct points, at the beginning, middle and end of the bed length. The height of the sludge layer was also measured with a ruler.

Plants monitoring

The cut of the aerial part of the Tifton 85 grass occurred approximately every 3 months, and the analysis of plant productivity was carried out for the SU through three random samplings of 1.0 m^2 at the beginning, middle and end of the bed. In addition, aspects such as alteration of color, wilting, height, presence of invasive species, death and attack of animals were monitored weekly.

Evaluation of the applicability of the sludge treatment system

The evaluation of the applicability of the CW treating septic tank sludge was carried out, in relation to the population served. This evaluation was carried out through primary data obtained from monitoring and secondary data from the literature.

RESULTS AND DISCUSSION

Hydraulic and solids loading rates

The raw sludge had a high variation during the monitoring, which was expected, since the origin of the trucks was different in each application, coming from different types of domestic facilities (houses, farms, condominiums, small trades and construction sites) and varied locations. With this, the quality of the sludge also varied considerably throughout the monitoring period, from visual aspects and presence of residues to the concentrations of the physical, chemical and biological parameters. Consequently, hydraulic and solids loading rates also varied considerably, resulting in an average of 13.1 m^3/m^2.year (6.3 - 21.4 m^3/m^2.year) and 81 kgTS/m^2.year (10.5 - 914.5 kgTS/m^2.year), respectively.

The solids loading rate obtained is lower than those reported in the literature, 125 to 250 kgTS/m^2.year (Koottatep et al., 2004) and 100 kgTS/m^2.year (Kengne et al., 2011), and can influence the quality of the percolated and post-treated liquid, as well as in the dewatering of accumulated sludge.

Sludge treatment and slurry after-treatment effect

The raw sludge and percolated liquid from the sludge and post-treatment unit showed high variation during the monitoring of the parameters. Bassan et al. (2013), who also found great variability in the clean-pit truck sludge samples, commented that this variation occurs due to factors such as storage duration, climate, type of system and the capacity of emptying of the truck.

The DO concentration in the raw sludge showed an average concentration of 0.5 mg/L and, as expected, in the percolated and in the post-treated liquids, DO concentrations were higher than those of the raw sludge. The concentrations found in the percolate were significantly lower than in the post-treated liquid, for α of 0.05, which may be associated to the aeration of the liquid that occurs in the pumping of the percolated liquid from the sludge unit to the post-treatment in the percolated unit. Regarding the pH values, for all the samples, the average was between 6.3 and 7.5, indicating a raw sludge, percolated liquid and post-treated liquid with neutral characteristics, which allows a better rate of microorganisms' growth. The temperature also showed little variation, with the averages being 27.1, 26.6 and 25.9°C for the raw sludge, percolated liquid and post-treated liquid, respectively.

Table 1 shows the concentrations and removal efficiencies of the other parameters analyzed. In general, it was possible to observe that, statistically, for a significance level of 5%, a significant difference in the concentration of all parameters (except bacteriological) was confirmed between the raw sludge (influent to the sludge unit) and the percolated liquid (effluent from the sludge unit). On the other hand, when evaluating the post-treated liquid, it was noticed that there was not an expressive increase in the improvement of the effluent quality in the percolation unit. At a significance level of 5%, no significant differences in the concentration of any of the parameters were observed in the post-treatment.

TABLE 1. Statistics on concentrations of raw sludge and percolated liquids (sludge unit effluent) and post-treated (percolate unit effluent) as well as the removal efficiencies in sludge and percolated units.

Parameter	Raw sludge		Percolated liquid				Post-treated liquid				Overall efficiency (%)
	Average	Standard deviation	Effluent		Efficiency (%)	p-level	Effluent		Efficiency (%)	p-level	
			Average	Standard deviation			Average	Standard deviation			
TS	2349	10358	1159	914	51	0.000169	1258	646	-	0.710474	46
VTS	1133	9440	545	534	52	-	618	366	-	-	45
COD	2937	7284	515	1316	82	0.000000	490	397	5	0.329341	83
BOD	1074	4355	246	433	77	0.000008	242	294	2	0.799805	77%
TKN	88	103	33	24	63	0.000001	24	21	27	0.132638	73
$N\text{-}NH_4^+$	82	52	29	23	65	0.000015	24	21	17	0.659008	71
Total coliforms	9.8 x10^{10}		1.6 x10^{11}		-	0.883492	8.7 x10^{10}		46	0.872859	11
Escherichia coli	3.6 x10^9		5.3 x10^9		-	0.783547	3.9 x10^9		26	0.863951	-

Obs.: removal efficiency calculated based on the averages of the influent and effluent concentrations. TS: total solids; VTS: volatile total solids; COD: chemical oxygen demand; BOD: biochemical oxygen demand; TKN: total Kjedahl nitrogen; $N\text{-}NH_4^+$: Ammonia nitrogen. Units: mg L^{-1}, except for total coliforms and *Escherichia coli*: MPN/100 mL.

Evaluating the characteristics of the raw sludge, a COD/BOD ratio of 2.73 was found, indicating that the biodegradable fraction was not high but still susceptible to biological treatment. When evaluating the volatile and fixed fractions of the raw sludge, by means of the VTS/TS ratio, 48% corresponded to the organic fraction and 52% to the inorganic fraction. This fact indicates that, although a good portion of the solids has already been stabilized, there is still a large percentage of organic matter. Bassan et al. (2013), in a study of the characterization of septic tank sludge, found a VTS/TS relation that varied in the samples from 53% to 61%, similar to that verified in this study.

According to Andreoli et al. (2007), for septic tank sludge, the typical range of dry solids concentration is 3 to 6%, and in this study an average value of only 0.23% was found for the raw sludge, that is, much more diluted. This greater dilution may be associated with several factors, such as the collection mechanisms of the clean-pit trucks, which usually also collect the liquid part of the septic tanks.

The highest concentration of nitrogen present in the raw sludge was in the reduced inorganic form of $N\text{-}NH_4^+$. According to Von Sperling (2007), ammonium is present due to the fact that, in the septic tank, hydrolysis and ammonification reactions take place.

Regarding the performance of the sludge unit, in relation to organic matter, the values of COD concentration in the percolate were similar to those found by Suntti et al. (2011), 88-507 mg/L, but the removal efficiencies were lower. Sonko et al. (2014) found COD removal efficiencies of 85-99%, but still high concentrations of 92-1853 mg/L. Panuvatvanich et al. (2009) found in the percolated liquid a BOD of 298 mg/L, close to that found in this study.

For the TS, the system removal efficiencies were also low when compared with other authors: removal of 99% of TS (Paing & Voisin, 2005) and removal of 94-96% of TS (Suntti et al., 2011).

Since the influent concentrations were lower than in most other studies, this also lead to lower removal efficiencies, for approximately the same effluent quality. Another possibility for this result may be the grain size of the filter; since Kuffour et al. (2009) found that the bed with sand of smaller granulometry (0.1-0.5 mm) produced an effluent twice less concentrated than that with larger granulometry (1-1.5 mm). In this study, the granulometry of the top layer was even larger (2.4-12.5 mm), because gravel was used and not sand. Vincent et al. (2011) commented that the substrate layer should guarantee a good filtering of the solids.

The system was originally designed as a system for the treatment of sewage, without adaptation for the reception of sludge. In addition, in some studies reporting good TS removal efficiency, such as those performed by Koottatep et al. (2004), the CWs were fed and the system outlet was kept closed, the liquid being retained in the system for six days, increasing the hydraulic holding time, which did not occur in this study, in which the outlet was kept open even in the moment of the batch pulse.

As for the nitrogen, the concentration values of TKN and $N\text{-}NH_4^+$ were similar to those found by Suntti et al. (2011), 14-39 mg/L and 11-22 mg/L respectively, but the removal efficiencies were lower. Sonko et al. (2014) found TKN concentrations of 43-66 mg/L, being slightly higher than the ones observed in this study. Analyzing statistically ($\alpha = 0.05$), the ammonium concentration significantly decreased from the raw sludge to the percolated liquid. When evaluating the performance of the percolate unit, in the post-treated liquid the average concentrations of both TKN and $N\text{-}NH_4^+$ were 24 mg/L, indicating that all N_{org} was removed. Part of the N_{org} can settle in the bed and be retained in the accumulated sludge, and later can be transformed into ammonia, by the process of mineralization. The ammonia can be adsorbed on the filter material and then oxidized to nitrate by the nitrification process.

As for the removal of organic matter, the post-treatment step was not important for the removal of nitrogenous matter.

Regarding the TC and *E. coli*, the system did not show improvement in the percolated or post-treated liquids. Tietz et al. (2007), in a study about vertical CW treating sewage, commented that the main factors contributing to the increase of the removal efficiency of total coliforms and *E. coli* are the porosity of the filter medium, the adsorption capacity of the filter medium and the hydraulic holding time. In this study, the low removal may be associated to the following facts: greater granulometry of the filter material, no permanence of the liquid inside the filter medium and protection of the bacteria from ultraviolet rays.

In the real scale analyzed, the percolation of the sludge unit received post-treatment in distinct units, which did not characterize a recirculation as such. However, the results obtained with pilot-scale tests (columns) to evaluate percolate recirculation to the sludge unit itself, at a significance level of 5%, showed no significant differences in the concentration of any of the monitored parameters.

In contrast, Lavrora & Koumanova (2010), in a study about the treatment of landfill leachate in CW, noticed that the higher the number of effluent recirculations, the better the removal efficiency of $N\text{-}NH_4^+$, BOD and COD. Foladori et al. (2013), in a study on CW treating sewage, found that recirculation allowed a progressive reduction of $N\text{-}NH_4^+$, and corresponding increase of $N\text{-}NO_3^-$, in addition to a higher efficiency of COD removal.

Cui et al. (2012), in a variant of the CW treating septic tank effluent, concluded that the efficiency of ammonia and total nitrogen increased with the frequency of recirculation, but the authors pointed out that, depending on other factors such as hydraulic loading rate, which resulted in one and two times of recirculation an increase of only 1-2% in the efficiency of total nitrogen removal.

Sludge accumulated on the surface of the sludge unit

Variations throughout the experiment at the height of the sludge layer of the CW have been observed. In the last measurement an average height of 8.8 cm and an annual accumulation rate of 7.3 cm/year were found. For Koottatep et al. (2004), the accumulation rate was 12 cm/year, but the solids loading rates in their research were superior.

55% of the accumulated sludge corresponded to dry solids (TS) and 45% to humidity, with a consistency of hard solid. There was a large difference in the percentage of total solids of the raw sludge, which was only 0.23%. Such increase in solids content indicates that the dewatering step occurred expressively in the CW. In tropical regions, according to Kengne et al. (2011), it is possible to achieve a percentage of dry solids of at least 30% in the treatment of sludge from septic tanks in CW. The application of the sludge in the CW was carried out weekly, there was no withdrawal of the accumulated material and the energy consumption was minimal. Regarding the stability of the sludge, the VTS/TS ratio was 0.60.

There was no clogging in the beds, which, according to Koottatep et al. (2004), is a consequence of the constant growth of the plant roots and the permanence of the dead roots in the sludge layer, because they help to maintain the porosity of the bed.

Plants in the sludge unit

There were no variations of the plants height along the unit size, indicating a homogeneous growth of Tifton 85 grass. For Brix (2014), the fact of not having plants across the bed surface is one of the most common problems observed in CW. The plants reached a maximum height of 83.1 cm.

In the literature, there is little information on the cut frequency of the Tifton 85 grass, being in this study of approximately 3 months, still occurring an episode in which cows and horses fed from the grass. Samples taken from two cuts in March and October/2014 were analyzed in the laboratory and resulted in a biomass of 1.04 and 1.43 kg of dry matter/m², respectively.

During the operation of the CW, the occurrence of invasive species was monitored, and for 3 months, from June to August/2014, the presence of some species was identified, which may originate from the raw sludge applied in the CW, or birds that inhabit the CePTS, where there were other plants. Initially, around 11% of the SU bed was occupied by the invaders, reaching 28% and, after 3 months, all invasive plants had already died. After, the Tifton 85 grass was already growing in their places again. In the other units, there was no presence of invasive species.

Applicability of the system

From the values of volumetric productions of sludge withdrawn from septic tanks cited by some authors, such as Strande et al. (2014) (1.5 L/inhab.day) and Andreoli et al. (2007) (0.3-1.0 L/inhab.day), the area of the CW under analysis (29.1 m²) and the volume of the received raw sludge (~ 8 m³/week), it is possible to estimate the number of people served in relation to volumetric production. The calculated values lead to a population equivalent of 1140 to 3799 inhabitants, considering the range of Andreoli et al. (2007), who are authors that worked in conditions similar to this study, which is important to understand the capacity of a system and its application. Therefore, in a small area of 29.1 m² of the sludge bed, sludge from septic tanks of a population between 1140 and 3799 inhabitants could be treated, which corresponds to the population range of several small localities in Brazil.

These values correspond to a range of 39 to 131 inhab/m² in the unit dedicated to the sludge (disregarding the post-treatment of the slurry). Therefore, the recommended system for the treatment of sludge is very compact.

This sanitation solution, in addition to being compact, is considered low cost and sustainable in the long term, according to Rulkens (2004) and Nielsen et al. (2014).

Plants grown in CW can be reused for other purposes, such as landscaping, handicrafts and animal feeding (Sonko et al., 2014) and the CW shows relevant advantages in relation to other technologies for sludge treatment, such as the non-removal of sludge accumulated in the bed in each application.

CONCLUSIONS

The system improved the quality of percolated liquid in terms of carbonaceous matter (average removal efficiency of 51% TS, 77% BOD and 82% COD) and nitrogen (average removal efficiency of 63% TKN and 65% $N\text{-}NH_4^+$), but showed, in general, lower removal efficiencies than those reported in the literature, which may be related to several design and operational characteristics of the CW, such as the less concentrated raw sludge, the larger granulometry of the filter medium and low hydraulic holding time. The post-treatment stage did not lead to better final effluent conditions, contrary to expectations, with no differences between the post-treated liquid and the slurry in the system. Likewise, the recirculation tested in the pilot units also did not show to be an important strategy for the improvement of the final effluent quality.

The dewatering of the accumulated sludge occurred satisfactorily, reaching a dry solids percentage of 55% and the VTS/TS ratio was 0.60, indicating good digestion of the sludge. There were no problems with clogging.

The Tifton 85 grass showed to be productive and resistant to the operational conditions of the system, surpassing the occurrence of invasive species.

These results reaffirm the vertical flow CW as an important technology for the treatment of septic tank sludge and can be considered a robust system for operational conditions that can occur in small communities.

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