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Biological systems coupled for treating wastewater from processing coffee cherries: I – Removal of organic matter

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ABSTRACT. Three treatment systems consisting of upflow anaerobic filters followed by constructed wetlands (CW) were evaluated in the treatment of wastewater from processing coffee cherries (WCP). The filters (F) were made up of PVC (1.5 m high and 0.35 m diameter) filled with gravel # 2 and SACs were made of wood boxes (1.5 m long, 0.4 m high and 0.5 m wide) sealed with HDPE geomembranes and filled with gravel 'zero'. WCP had the pH adjusted with lime to values close to 7.0 and the nutrient concentration changed to obtain a BOD/N/P ratio equal to 100/5/1. As a result, the values of influent and effluent pH remained within the range appropriate to the biological degradation of organic material. The system could not bear the shock of the organic load, which reduced the organic matter removal efficiency. Based on the analysis of performance and operating conditions employed, only the system that received the lowest organic load (F_1+CW_1) on the third phase, was effective in removing organic matter.

Keywords: anaerobic reactor, constructed wetlands, agroindustrial wastewater, coffee.

Sistemas biológicos combinados para o tratamento de águas residuárias do processamento dos frutos do cafeeiro: I – Remoção de matéria orgânica

RESUMO. Três sistemas de tratamento, compostos por filtros anaeróbios com escoamento ascendente, seguidos por sistemas alagados construídos (SAC), foram avaliados operacionalmente no tratamento da água residuária do processamento dos frutos do cafeeiro (ARC). Os filtros (F) foram confeccionados em PVC (1,5 m de altura e 0,35 m de diâmetro) e preenchidos com brita número 2 e os SACs foram constituídos por caixas de madeira (1,5 m de comprimento, 0,4 m de altura e 0,5 m de largura) impermeabilizados por geomembrana de PEAD e preenchidos com brita número "zero". A ARC teve o pH corrigido com cal até valores próximos a 7,0 e a concentração de nutrientes alterada de forma a se obter uma relação DBO/N/P igual a 100/5/1. Como resultado, observou-se que os valores de pH afluente e efluente mantiveram-se dentro da faixa de valores adequados para que ocorresse a degradação biológica do material orgânico. Os sistemas não suportaram o choque de carga orgânica, o que reduziu sua eficiência de remoção. Com base na análise de desempenho e nas condições operacionais empregadas, apenas o sistema que recebeu a menor carga orgânica (F_1+SAC_1), na terceira fase, foi eficaz na remoção de matéria orgânica.

Palavras-chave: reator anaeróbio, sistemas alagados construídos, águas residuárias agroindustriais, café.

Introduction

In 2012 Brazil harvested about 50 million bags of coffee, with this production concentrated in the southeast of the country, highlighting the States of Minas Gerais, Espírito Santo and São Paulo, which together account for over 88% national production. The Brazilian coffee production is one of the most competitive worldwide, placing the country first on the world ranking of production and export of grain (CONAB, 2012).

Before an increasingly demanding market, the search for quality is nowadays a major concern in several production segments and especially in the coffee agribusiness. The quality is essential for the product to gain market and meet the new requirements of internal and external consumers. Given this, the Brazilian producer should specialize in producing a high quality coffee if wants to engage a profitable coffee production.

In this context, besides maintaining the quality potential of the newly harvested coffee, the washing and wet processing in which the coffee is submitted to peeling, washing and degumming or partial removal of the mucilage before drying, reduce the energy cost of the process. Despite of all advantages, washing and wet processing of coffee fruits generate large volumes of wastewater, with high pollution potential, requiring a previous treatment before the discharge into water bodies (MATOS et al., 2007).

Several researches (BELLO-MENDOZA; CASTILLO-RIVERA, 1998; BRUNO; OLIVEIRA, 2008; FIA et al., 2010a; PRADO; CAMPOS, 2008; SILVA et al., 2010; SILVA et al., 2011) have focused on the treatment of this wastewater using anaerobic systems, which have the advantage of requiring a smaller area. Nevertheless, although anaerobic treatment processes present large removal of biodegradable organic matter, with relatively low cost, their effluents have not met the requirements of environmental legislation, requiring thus a post-treatment. As an alternative of post-treatment of effluents from anaerobic reactors, researchers have reported and proposed the use of constructed wetlands (BRASIL et al., 2005; FIA et al., 2010b; SOUSA et al., 2004; SOWMEYAN; SWAMINATHAN, 2008).

In this way, the present study aimed at evaluating the performance of treatment systems made up by anaerobic filters followed by constructed wetlands, subjected to different organic loads, in treating wastewater from processing coffee cherries.

Material and methods

The experiment was conducted in the Department of Agricultural Engineering, Federal University of Viçosa (UFV), Viçosa, Minas Gerais State, at geographical coordinates 20º45'S and 42º52'W, and mean altitude of 650 m above sea level. According to Köppen classification, the climate is Cwa type, high altitude tropical climate, with rainy summer and dry winter.

Three anaerobic filters were made up of PVC pipes (0.35 cm diameter and 1.5 m length) with total capacity of 135.5 L (Figure 1A). These units were filled with support media (granite-gnaisse crushed stone #2), forming 1.0 m height columns above the false bottom, which was 0.2 m distant from the bottom. As inoculum, it was used 50 L sludge from the anaerobic tank for treating swine wastewater of the UFV.

The effluents of the three filters (F_1, F_2 and F_3) were released into three respective CW (CW_1, CW_2 and CW_3) of horizontal subsurface flow, constructed on a pilot scale, consisting of wooden boxes (0.4 m height x 0.5 m wide x 1.5 m long), waterproofed by high density polyethylene (HDPE) geomembranes placed on 0.01 m m^{-1} sloped soil. As support media, it was used gravel #0 (diameter D_{60} = 7.0 mm and initial void volume of 0.491 m^3 m^{-3}). CW were filled with gravel up to 0.35 m height, leaving a 0.05 m free edge (unsaturated), since the water level was kept at 0.30 m (Figure 1B and C). In each CW, it was planted on the first 0.75 m of the bed the species *Alternanthera phyloxeroides* and on the last 0.75 m the species *Typha* sp. (MATOS et al., 2010).

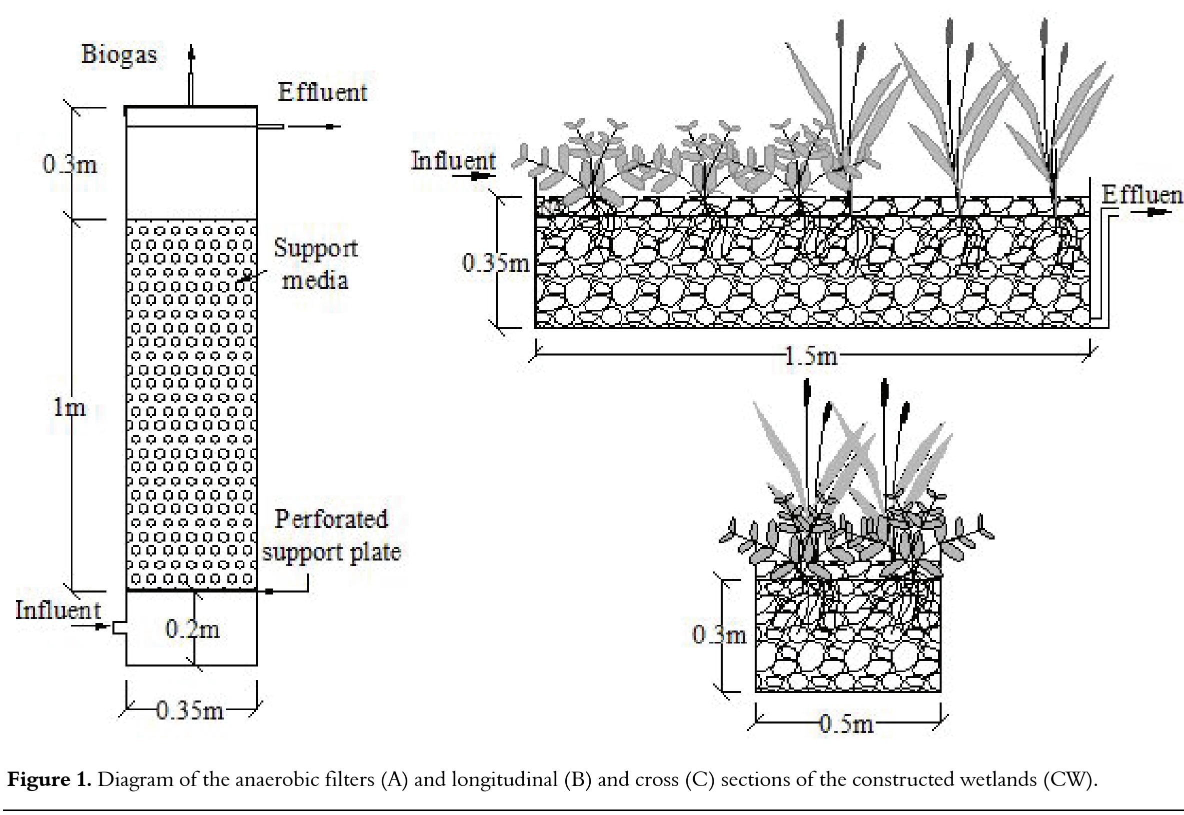

Figure 1. Diagram of the anaerobic filters (A) and longitudinal (B) and cross (C) sections of the constructed wetlands (CW).

The system was operated at room temperature and evaluated for 130 days, between June and October, and divided into three operating phases (42, 46 and 42 days, respectively).

In the starting period of the system, also called first phase of operation, filters were fed simultaneously with the same influent (diluted WCP, in which the pH was adjusted with lime ($Ca(OH)_2$) to values close to 7.0). From the second phase, there was a differentiated increase in the organic load applied to the filters, taking as reference the chemical oxygen demand (COD). The application of the WCP into the F_1 and F_2 was made in diluted form, in the proportions of 50 and 75% (v/v), respectively, while the F_3 received WCP without dilution, maintaining constant the hydraulic retention time (HRT).

From the second phase, in addition to pH correction, it was performed the nutrient correction of the WCP, by using urea and simple superphosphate, to achieve the ratio 100/5/1 between biochemical oxygen demand, nitrogen and phosphorus (BOD/N/P) (METCALF; EDDY, 2003). On the third phase, the same proportions of WCP was kept in the feeding of the three filters, but increased approximately twice the HRT of the filters and of CW.

Mean values and standard deviation of the operational characteristics of the anaerobic filters and of the CW are listed in the Table 1.

Once a week influent and effluent samples were taken from the filters and effluents of the CW for evaluating the pH; BOD, by the iodometric method; COD, by the open reflux method; and total solids (TS) and total suspended solids (TSS), by the gravimetric method (APHA; AWWA; WEF, 2005). The temperature of the liquid was measured daily with an analog mercury thermometer.

A completely randomized design was adopted with three systems (F + CW) and three phases and with a number of repetitions equal to the number of samplings. Then an analysis of variance was performed, being the mean values compared by a Tukey's test at 5% probability. For all analyses it was used the statistical package SAEG® (RIBEIRO JÚNIOR, 2001).

Results and discussion

The system operated at room temperature that varied between 3.4 and 36.1°C. In the phases I, II and III, average daily temperatures of the liquid were 17.6, 18.4 and 20.4°C, being this temperature range considered psychrophilic for microorganisms.

The anaerobic digestion within the psychrophilic range (0 - 20°C) is interesting for treating wastewater that have as intrinsic characteristic low temperature or liquid effluents produced in period of low temperatures. The rise in the temperature of effluent produced under psychrophilic conditions for mesophilic or thermophilic conditions and its maintenance in these conditions imply in energy expenditure and consequently higher costs of treatment (LETTINGA et al., 2001). However, under low temperatures there is need of a longer retention time of biomass, reactors with larger volumes, and lower concentrations of organic matter.

Table 1. Operational characteristics of the anaerobic filters and of constructed wetlands.

Treatment units	Q	HRT	OLR	TCO_A
			Phase I	
F_1	0.052 ± 0.018	33.5 ± 10.9	1.49 ± 0.61	-
CW_1	0.048 ± 0.005	58.7 ± 7.4	-	1058 ± 586
F_2	0.053 ± 0.020	32.3 ± 9.1	1.82 ± 0.73	-
CW_2	0.049 ± 0.004	57.6 ± 5.0	-	805 ± 280
F_3	0.049 ± 0.023	37.1 ± 12.2	1.77 ± 0.95	-
CW_3	0.049 ± 0.008	58.6 ± 9.9	-	798 ± 409
			Phase II	
F_1	0.050 ± 0.017	35.1 ± 12.8	5.60 ± 2.26	-
CW_1	0.056 ± 0.018	54.4 ± 13.7	-	3597 ± 1165
F_2	0.051 ± 0.016	34.2 ± 11.5	8.30 ± 2.55	-
CW_2	0.048 ± 0.010	61.0 ± 13.4	-	6006 ± 1635
F_3	0.047 ± 0.015	37.2 ± 12.2	12.99 ± 6.84	-
CW_3	0.050 ± 0.012	59.5 ± 14.2	-	9092 ± 4559
			Phase III	
F_1	0.031 ± 0.011	56.4 ± 18.4	1.69 ± 0.57	-
CW_1	0.027 ± 0.007	111.8 ± 27.0	-	1507 ± 213
F_2	0.029 ± 0.007	56.9 ± 13.7	3.24 ± 0.88	-
CW_2	0.023 ± 0.005	126.7 ± 24.1	-	22579 ± 793
F_3	0.032 ± 0.011	54.1 ± 16.1	3.86 ± 1.27	-
CW_3	0.025 ± 0.005	114.7 ± 22.5	-	3043 ± 1076

Q – flow (m^3 day^{-1}); HRT - hydraulic retention time (h); OLR – volumetric organic load rate (kg m^{-3} day^{-1} COD); OLR_S – organic loading rate based on surface area (kg ha^{-1} day^{-1} COD). Five samples were taken at each phase for calculation of OLR and OLR_S, Q and HRT were monitored daily.

Variations in wastewater temperature may also affect the performance of treatment in CW, where biological processes are highly dependent on the temperature, affecting the removal of soluble organic matter and nitrogen (KADLEC; WALLACE, 2008).

In relation to rainfall events, during the experimental period it was only registered a rainfall of 15.4 mm, on the 121st day after starting the experiment, which was not able to influence the results, regarding the increase in volume of the effluent under treatment, and consequent dilution, which could lead to lower concentrations of effluents of the systems.

In the Table 2 are presented the mean values of pH, COD, BOD, TS and TSS influent to the system (C1, C2 and C3) and effluent from the filters (F_1, F_2 and F_3) and from the CW (CW_1, CW_2 and CW_3) and in the Table 3 are shown the mean values of removal of COD, BOD, TS and TSS in F+CW systems.

A downward trend in the values of pH in the effluents of the filters was observed, compared with those of the influents, during the second and third phases in the F_2+SAC_2 and F_3+SAC_3. Nevertheless, values remained within suitable range for anaerobic digestion (CHERNICHARO, 2007). Bruno and Oliveira (2008) verified a sharp reduction in pH values of effluents of UASB reactors in two stages of WCP treatment, when it was applied OLR of 5.8 and 3.6 kg m^{-3} day^{-1}, with a greater reduction in the higher OLR applied.

Variations in the influent flow (data not shown) caused fluctuations in the system stability. In this way, it was not obtained constant removal efficiencies, during the three experimental phases. During the first phase, mean removals for COD and BOD were similar among the three systems ($p > 0.05$). Prado and Campos (2008), treating WCP in UASB reactors, have obtained a removal of BOD and COD between 45 and 95%, and 33 and 93%, respectively. Bruno and Oliveira (2008) applied OLR of 5.8 kg m^{-3} day^{-1} COD in first stage UASB reactor and have attained removal efficiency for COD of 55%. However, these authors worked in laboratory, an environment less susceptible to climatic variations. Therefore probably they achieved greater organic matter removal efficiency even with larger OLRs, compared with those evaluated in the present study.

With increased organic load applied in the phase II, there was a reduction in mean removal efficiency for BOD and COD in the systems F_2+CW_2 and F_3+CW_3. Bello-Mendoza and Castillo-Rivera (1998) obtained a drastic reduction in the efficiency of anaerobic reactor (22%) when increased the OLR from 1.89 to 2.59 kg m^{-3} day^{-1} COD. Nevertheless, no efficiency reduction was observed for the F_1+CW_1.

Table 2. Mean values and standard deviation of pH, chemical oxygen demand (COD), biochemical oxygen demand (BOD), total solids (TS) and total suspended solids (TSS) of the influent (C_1, C_2, C_3) and effluent of anaerobic filters (F_1, F_2, F_3) and constructed wetlands (CW_1, CW_2, CW_3).

Treatment units	pH	COD	BOD	TS	TSS
			Phase I		
C_1	6.69 ± 0.43	1985 ± 908	1292 ± 474	2487 ± 1642	166 ± 139
F_1	7.05 ± 0.49	1430 ± 657	1019 ± 505	1763 ± 617	56 ± 43
CW_1	7.21 ± 0.38	748 ± 409	473 ± 382	1344 ± 354	34 ± 8
C_2	6.80 ± 0.45	2109 ± 943	1401 ± 509	2610 ± 1125	135 ± 82
F_2	7.07 ± 0.42	1248 ± 388	965 ± 300	1873 ± 598	61 ± 41
CW_2	7.25 ± 0.31	824 ± 389	537 ± 317	1371 ± 742	25 ± 21
C_3	6.81 ± 0.59	2140 ± 955	1183 ± 408	3036 ± 2711	126 ± 83
F_3	6.98 ± 0.37	1267 ± 628	722 ± 366	1867 ± 500	97 ± 53
CW_3	7.36 ± 0.59	736 ± 487	384 ± 283	1474 ± 702	30 ± 13
			Phase II		
C_1	6.60 ± 0.55	6740 ± 1215	3242 ± 771	7079 ± 2128	295 ± 188
F_1	6.73 ± 0.54	5669 ± 1176	2938 ± 818	4221 ± 574	165 ± 15
CW_1	7.39 ± 0.18	1881 ± 398	787 ± 303	2175 ± 537	78 ± 31
C_2	6.91 ± 0.56	11854 ± 2641	4178 ± 781	9473 ± 1826	407 ± 257
F_2	6.38 ± 0.12	9666 ± 2098	3790 ± 630	7709 ± 1160	180 ± 27
CW_2	6.95 ± 0.19	7096 ± 3826	3556 ± 1744	3957 ± 1909	94 ± 52
C_3	6.84 ± 0.62	19656 ± 8282	5874 ± 1019	13403 ± 3353	675 ± 455
F_3	6.30 ± 0.19	17246 ± 7864	3318 ± 1111	9123 ± 2898	269 ± 36
CW_3	6.49 ± 0.51	14274 ± 10021	2247 ± 1189	5942 ± 3814	159 ± 80
			Phase III		
C_1	7.45 ± 0.61	4253 ± 730	2500 ± 1241	2660 ± 501	170 ± 19
F_1	7.74 ± 0.12	1669 ± 1081	1336 ± 1105	1841 ± 754	87 ± 33
CW_1	7.71 ± 0.26	587 ± 323	359 ± 283	1306 ± 457	48 ± 22
C_2	7.82 ± 0.17	6946 ± 523	3250 ± 972	5530 ± 697	81 ± 40
F_2	7.35 ± 0.37	5549 ± 1312	2772 ± 874	3659 ± 597	102 ± 22
CW_2	7.84 ± 0.11	1786 ± 1066	1355 ± 1144	2116 ± 466	61 ± 29
C_3	7.87 ± 0.22	9230 ± 1255	4399 ± 1012	6870 ± 1780	92 ± 27
F_3	7.13 ± 0.51	7828 ± 1303	1617 ± 1337	4316 ± 1404	134 ± 43
CW_3	7.50 ± 0.23	5940 ± 2789	1085 ± 879	3802 ± 1345	89 ± 38

COD, BOD, TS and TSS in mg L^{-1}.

Table 3. Mean removal efficiency (%) for chemical oxygen demand (COD), biochemical oxygen demand (BOD), total solids (TS) and total suspended solids (TSS) by the treatment systems consisting of anaerobic filters followed by constructed wetlands (F+CW), in the three phases of system operation.

Variables	F_1+CW_1			F_2+CW_2			F_3+CW_3		
	I	II	III	I	II	III	I	II	III
COD	55A	70A	85A	57A	40B	75B	59A	22B	32C
BOD	57A	73A	86A	57A	12B	61B	65A	6B	39B
TS	28A	67A	52A	38A	56A	62A	21A	50A	45A
TSS	63A	67A	72A	81A	74A	24B	66A	67A	1C

For the same variables, within the column of each phase, means with the same capital letter are not significantly different by Tukey's test at 5% probability.

Despite increased organic load in F_1+CW_1, the applied values probably were not enough to destabilize the system. In treatment units adapted to the effluent to be treated, the increase in organic load leads to increased removal rates of organic matter. Jing et al. (2002) in the treatment of domestic sewage in CW, found a relationship close to linearity between the increase in load (62 – 149 kg ha^{-1} day^{-1} COD) and increase in organic matter removal rates (76 to 89%). Also in CW used in treating water from leather processing, Calheiros et al. (2007) verified a linear relationship between applied load (332 to 1.602 kg ha^{-1} day^{-1} COD) and obtained efficiency (54 to 73%).

There was a trend of recovery of treatment systems in the phase III and this was due to increased HRT and consequent reduced OLR applied. Moreover, a reduction in COD of WCP used to feed the filters was observed, due to the period of storage.

During the third phase, the F_1+CW_1 presented mean removal efficiency for COD and BOD considered reasonable for systems with high load and under psychrophilic conditions and statistically different from the others ($p < 0.05$). Brasil et al. (2005) used CW in the treatment of domestic sewage pre-treated in septic tank and registered a mean removal efficiency for COD of 87%. Meanwhile, organic loads applied to CW were much lower than in this study, being the mean equal to 285 kg ha^{-1} day^{-1} COD.

Fia et al. (2010b) obtained lower removal efficiency for COD (58 and 79%) and BOD (38 to 71%) in treatment systems of WCP made up by anaerobic filter followed by CW cultivated with oat and ryegrass, despite the lower organic loads applied by these authors (1.9 to 4,9 kg m^{-3} day^{-1} COD and 650 to 1,530 kg ha^{-1} day^{-1} COD).

Masbough et al. (2005) detected removal of 51 to 63% for BOD in the treatment of cellulose leachate, in wetlands with HRT of 7 days, and BOD ranging from 1,700 to 3,460 mg L^{-1}. Authors have observed greater pollutant removal efficiency in those cells that received the leachate with pH correction (6.0) and nutrient addition (N, P and K). Tao et al. (2006) also treated leachate from cellulose processing plant and concluded that 0.4 kg m^{-3} day^{-1} COD (1,000 kg ha^{-1} day^{-1} COD, approximately) is the maximum organic loading rate to be applied in SACs without inhibiting the microbiota. The authors concluded that an increase in HRT could lead to enhanced organic matter removal efficiency of wastewater.

During the phase I, by being a period for system adjustment, there was a drag of sludge both by flow instability and greater amount of microbial cells not attached to the support material. A higher turbulence causes a greater displacement and removal of the biofilm, implying in greater content of solids in liquid phase and probably greater content of extracellular polymeric substances.

The loss of solids, observed in the three phases, can also be justified by the wash out of biomass, owing sudden hydraulic variations and lower settling of solids, under low temperature, since the fluid viscosity remains high, resulting in slower sedimentation of the produced biomass, especially microorganisms with suspended growth (LETTINGA et al., 2001).

Values higher than obtained herein were observed by Bruno and Oliveira (2008) who obtained between 70 and 91% of removal of TSS in the first stage UASB reactor. According to Lettinga et al. (2001), anaerobic filters have reasonable performance as for removal efficiency of suspended solids, when applied small solids loadings.

A remarkable reduction was detected for the TSS concentration in the ARC discharged in the treatment system, caused by the addition of lime, which led to coagulation/flocculation of the suspended particulate matter, promoting the sedimentation of these particles and consequent clarification of the WCP. On the third phase, the reduction in the solid removal efficiency in some systems can be caused by the saturation of the system, and also due to the cutting of the plants grown in the CW, which may have caused the senescence of the root system and carried to outside the system (FIA et al., 2008).

In agreement with Brasil et al. (2005), part of the suspended solids is incorporated to the microbial mass developed in the medium, and other part is accumulated in the CW, and probably the solids remaining in the effluent are not part of those discharged in the system, but certainly are material converted or produced in the medium. The decrease in solid removal efficiency over time can be related to decay of the accumulated organic matter which, as reported by Bavor et al. (1989), has seasonal cycle in processes of accumulation and release of solids.

Fia et al. (2010b) when using anaerobic filters followed by CW cultivated with oat and ryegrass obtained between 8 and 44% of TS and between 70 and 85% of removal for TSS. Similarly to that observed in most systems evaluated in this study, the system F+CW evaluated by Fia et al. (2010b) also presented greater removal efficiency of TSS compared with removal efficiency of TS.

The system F_1+SAC_1 achieved in the phase III, a mean removal efficiency for COD and BOD above 85%, which meet the environmental legislation for disposal of effluents into water bodies, once it does not change the quality of the receiving water body (COPAM, 2008). However, this is the first study using systems composed of anaerobic filters followed by CW in the treatment of WCP and the results are very promising, especially those obtained with F_1+CW_1. Previously, only studies related to anaerobic digestion and discharge of this water in the soil could be found in literature.

The results of the present study emphasize the need to increase the HRT of systems, to increase the organic matter removal efficiency and consequently produce effluents with conditions to be disposed in the environment, since it is not allowed the dilution of wastewater to favor its treatment.

Once the WCP used in this study came from the processing of coffee cherries with recycling of wastewater in the process, the values of organic matter were relatively high, implying in longer times of hydraulic retention for satisfactory removal of the organic content and consequently in greater units for treating. A set of systems evaluated herein (F_1+CW_1, for instance) could treat around 30 L WCP per day or approximately the WCP produced in the processing of 12 L fruits. In this way, further researches should be conducted in order to obtain design parameters for wastewater treatment.

Conclusion

The hydraulic retention times exceeding 160h, during the phase III, have promoted greater removal efficiencies for COD and BOD, when compared with hydraulic retention times of approximately 90 hours, except for the system F_3+SAC_3.

The hydraulic retention time of approximately 160 hours was not enough for F_2+CW_2 and F_3+CW_3 to produce effluents that meet standards for disposal in water bodies, according to the environmental legislation of the Minas Gerais State.

The system F_1+CW_1 that received the smallest organic load, presented a satisfactory performance relative to organic matter removal, reaching 85 and 86% of removal for BOD and COD.

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