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Influence of flow direction in the performance of anaerobic filters

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ABSTRACT. This work aimed to evaluate the performance of similar anaerobic filters operating with opposite wastewater flows, and compare mathematical models that describe the kinetics of organic matter degradation in both. Two pilot-scale filters were fed with domestic effluent – one filter worked as upflow (UAF) and the other as downflow (DAF). Experimental COD data obtained from samples taken along the length of the filters were used to fit the first-order mathematical model, the model proposed by Leduy and Zajic (1973) and the model proposed by Brasil et al. (2007). The first model showed overestimated reaction constant (k) values when compared to those obtained using the other models. The models proposed by Brasil et al. (2007) and Leduy and Zajic (1973) presented the highest coefficients of determination (R^2). The average removal efficiencies of total COD were equal to 68 and 79% for UAF and DAF, respectively. The results revealed no significant differences between the two filters with regard to the variables applied.

Keywords: kinetics, anaerobic upflow reactor, anaerobic downflow reactor, domestic wastewater.

Influência do sentido de escoamento no desempenho de filtros anaeróbios

RESUMO. Com a realização deste trabalho, objetivou-se avaliar o desempenho de filtros anaeróbios similares operando com sentido inverso de escoamento da água residuária, além de comparar modelos matemáticos descritivos da cinética de degradação de matéria orgânica em ambos os filtros. Dois filtros, construídos em escala piloto, foram alimentados com esgoto doméstico, sendo um com escoamento ascendente (UAF) e outro com escoamento descendente afogado (DAF). A partir de valores de DQO obtidos em amostras coletadas ao longo do comprimento dos filtros, foram ajustados o modelo matemático de primeira ordem, o modelo proposto por Leduy e Zajic (1973) e o modelo proposto por Brasil et al. (2007). O primeiro modelo apresentou valores de constante de reação (k) superestimados em relação aos obtidos utilizando-se os demais modelos. Os modelos propostos por Brasil et al. (2007) e por Leduy e Zajic (1973) foram os que apresentaram maiores coeficiente de determinação (R^2). As eficiências médias de remoção de DQO total foram iguais a 68 e 79% para UAF e DAF, respectivamente. Os resultados não evidenciaram diferenças significativas entre os dois filtros em relação às variáveis avaliadas.

Palavras-chave: cinética, reator anaeróbio de escoamento ascendente, reator anaeróbio de escoamento descendente, esgoto doméstico.

Introduction

Environmental sanitation is an essential factor for improving the health and quality of life of a given population, as well as for environmental preservation. Among the actions comprising environmental sanitation are the collection and treatment of wastewater (GALVÃO JUNIOR; PAGANINI, 2009). An adequate sewage treatment system must be economically viable, efficient, compatible with the local reality and easy to operate. One type of sewage treatment unit that combines these characteristics is the anaerobic filter, used in communities where the wastewater collection grid is not present (MANARIOTIS; GRIGOROPOULOS, 2006).

Anaerobic filters are reactors filled with a layer of support material (bed), on which microorganisms are fixed, forming biofilm. Water flow – upflow or downflow – occurs in the crevices of the bed formed by the support material, on which also proliferate microorganisms that can collect as granules and flakes (SINGH; PRERNA, 2009). The fact that the biomass attaches to a support material provides improved and more consistent performance of anaerobic filters compared to the removal of organic matter in effluent treatment when compared to UASB reactors (JAWED; TARE, 2000).

The preferred filling material for anaerobic filters has been size-4 gravel, a material with high specific weight requiring more resistant and costly structures if upflow is chosen, because of the need for a 'false bottom' at the base of the filter. Nevertheless, anaerobic filters can operate using either upflow or downflow; the latter is more recommended when wastewater features high levels of suspended solids, as it involves a lower probability of clogging the support medium compared to upflow filters (JAWED; TARE, 2000; SÁNCHEZ et al., 2005). According to Andrade Neto et al. (2001), submerged downflow filters appear to be functionally similar to upflow filters, but feature certain operational advantages and reduced construction costs.

The importance of anaerobic digestion as a wastewater treatment process has grown substantially in recent decades, especially by presenting a more favorable energy balance than conventional aerobic processes (LIER et al., 2001). Anaerobic processes generate energy in the form of biogas and produce sludge in significantly lower quantities than those produced by aerobic treatment processes. Moreover, they require a lower amount of energy when compared to aerobic treatment systems (such as activated sludges, for instance) and sludge management is reduced due to the smaller quantities produced (LEITÃO et al., 2006).

One of the most important mechanisms for removing organic material and other pollutants in biological treatment systems is bacterial metabolism, which leads to the transformation of certain substrates, substances or compounds by microbial action. This method has been the focus of intense study by researchers interested in mathematically modeling that process to predict system performance (KAPDAN, 2005).

The most frequently used kinetic relationship to describe the hydrolysis process has been the first-order model (BATSTONE, 2006), featuring a reaction rate directly proportional to substrate concentration, given that the velocity of a reaction catalyzed by enzymes increases according to substrate concentration, until reaching maximum velocity.

Kinetic data, in addition to providing information on substrate growth and use by several cultures, can be useful to analyze the treatment system and reactor scaling. As such, the kinetic and operational parameters can be equated to verify the relationships between those parameters, and consequently the influence of kinetics on the operation (MORAES; PAULA JÚNIOR, 2004). That analysis can be obtained through mass balance in biochemical reactors used for wastewater treatment.

Considering that construction ease and costs are factors of vital importance to further disseminate the practice of adequate treatment of domestic effluents, the objective of this study was to evaluate the performance of similar anaerobic filters operating with wastewater upflow and downflow, as well as to compare descriptive mathematical models for degradation kinetics of organic matter in both filters.

Material and methods

Two filters were built using pieces of PVC pipe, 0.35 m in diameter and 1.5 m long, with total volume of 0.140 m^3 and useful volume of 0.090 m^3. Prior to the start of the experiment, the filters were used to treat wastewater from coffee fruit processing (FIA et al., 2011), knowingly featuring lower organic concentration and easier degradation than that of wastewater from coffee fruit processing. The filters were fed with domestic sewage, one filter with upflow (UAF) and the other with submerged downflow (DAF). Both filters were filled with support material (size-2 gravel), with a 1.0 m high support medium column over the false bottom (0.2 m high) in UAF and 1.2 m high in DAF. In each filter, about 3 L of sludge were kept from that generated in the treatment of wastewater from coffee fruit processing with 33.5 g L^{-1} of total volatile solids (TVS). Raw domestic sewage first passed through a preliminary treatment (degritter, grease trap and homogenizer) prior to being applied in the filters. The anaerobic filters were operated and evaluated during 100 days, between the months of March and July, at ambient temperature. The mean operational characteristics of the filters are shown in Table 1.

Table 1. Mean operational characteristics and standard deviations of anaerobic filters.

Variables	UAF	DAF
Q	0.078±0.021	0.073±0.023
HRT	0.98±0.33	1.00±0.28
OLR	0.472±0.285	0.472±0.295
OLR_B	0.05	0.05

In which: Q – flow (m^3 day^{-1}); HRT - hydraulic retention time (day); OLR – organic loading rate (kg m^{-3} day^{-1}); OLR_B – biological organic loading rate measured as [BOD] $[TVS]^{-1}$ $[day^{-1}]$ (kg kg^{-1} day^{-1}); UAF – upflow anaerobic filter; DAF – submerged downflow anaerobic filter.

Filters were monitored by analyzing affluent and effluent, totaling 13 one-time samplings, in which bicarbonate alkalinity (BA) and total volatile acids (TVA) were quantified through potentiometry, as described by Ribas et al. (2007); chemical oxygen demand (COD) was assessed using the open reflux method; and the concentration of total solids (TS) and total suspended solids (TSS) by the gravimetric method (APHA et al., 2005). The study measured pH as well, using a bench pH meter. Data were analyzed and means compared through Tukey's test, adopting a 5% probability levels, using the SAEG® statistical package.

To comparatively evaluate the kinetic models applied on the experimental data, three collections were made at the end of the monitoring period, in order to quantify COD at three sampling points along the height of the filters, spaced 0.20 m apart, as well as at the entrance and exit of the systems. Later, first-order kinetic models (BATSTONE, 2006), first-order models with residual concentration (LEDUY; ZAJIC, 1973) and first-order models modified by Brasil et al. (2007) (Table 2) were fit to the data. The parameters of the models were estimated by non-linear regression (Levenberg-Marquardt method).

Table 2. Models evaluated in this work.

Models	Equations	Parameters
1st Order	$C_e = C_a \cdot e^{(-k \cdot HRT)}$	C_e = effluent concentration ($M L^{-3}$); C_a = affluent concentration ($M L^{-3}$);
Leduy and Zajic (1973)	$C_e = C_r + (C_a - C_r) \cdot e^{(-k \cdot HRT)}$	HRT = hydraulic retention time (T); k = first-order reaction constant (T^{-1});
Brasil et al. (2007)	$C_e = C_a \cdot e^{(-k \cdot HRT^n)}$	C_r = residual concentration ($M L^{-3}$); n = equation constant.

Results and discussion

Filter performance

During the monitoring period, pH values ranged from 6.8 to 7.5 in the affluent and 6.7 to 7.6 in filter effluents, remaining close to neutrality overall. Starting on the 27th day of monitoring, the bicarbonate alkalinity (BA) in filter effluents remained constantly higher than that of the affluent. This indicates that, after that period, microorganisms had already adapted to the sewage affluent in the filters (Figure 1), whereas the concentration of volatile acids (TVA) in the effluents was always lower than that obtained in the affluent. The TVA/BA ratio was lower than 0.5 in both filters. This indicates that the degradation process had favorable conditions, without risk of acidification (UMANÃ et al., 2008).

Figure 2 presents the concentrations of total affluent and effluent COD of the filters, and filtered effluent COD of the filters. It can be observed that the filters mitigated the load variations of affluent organic matter, enabling more stable effluents.

Table 3 presents the mean concentration values of total COD, filtered COD, total suspended solids (TSS) and total solids (TS), with the respective removal percentages of organic matter and solids of the anaerobic filters. The filters provided satisfactory results for the removal of total COD and filtered COD. Although there was a tendency for greater removal efficiency of organic matter in DAF, especially for the total COD fraction, there was no significant difference ($p > 0.05$) between them. With regard to removal of the soluble fraction, a greater proximity was observed between the removal efficiency values for both filters, evidencing greater drag of solids in UAF, which showed greater variation of flow (data not shown). This can also be confirmed comparing the values of effluent solids in the filters: there is a higher mean concentration in UAF effluents, although there is no statistical difference ($p > 0.05$) between the values.

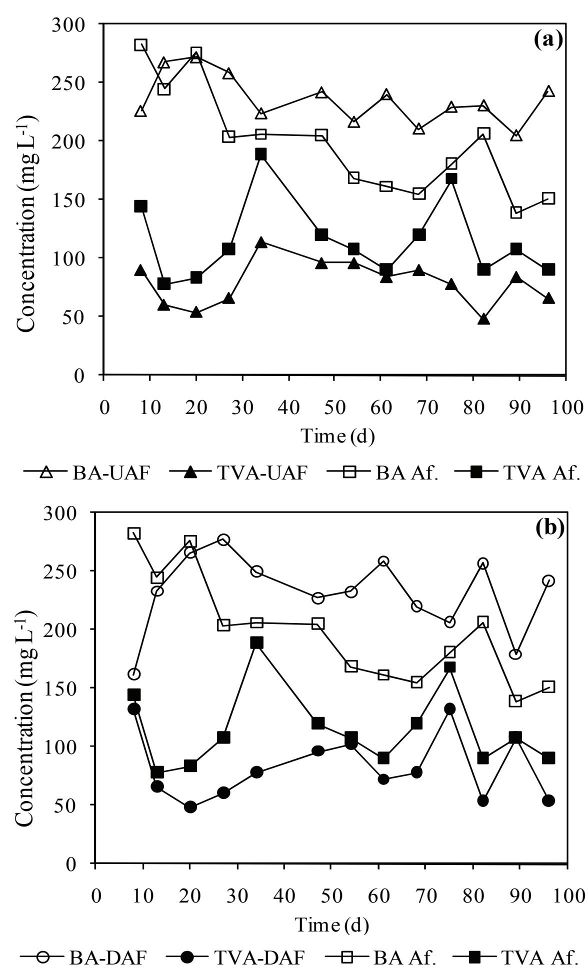

Figure 1. Concentration of BA (mg L^{-1} of $CaCO_3$) and TVA (mg L^{-1} of acetic acid) in the affluent (Af.) and effluents in the anaerobic flow filters: (a) upflow (UAF) and (b) submerged downstream (DAF).

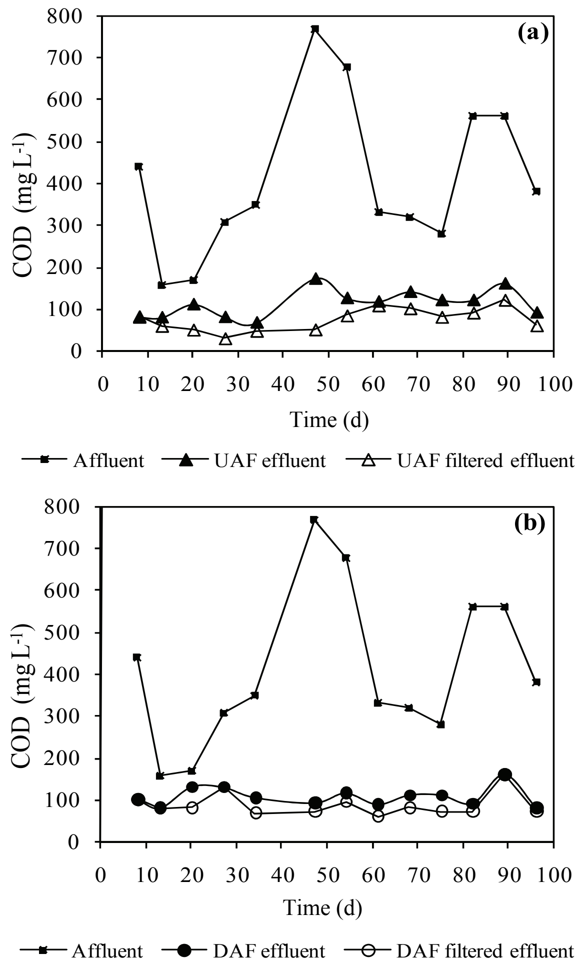

Figure 2. Concentrations of total affluent and effluent COD of the filters and filtered effluent COD of the anaerobic filters with flow: (a) upflow (UAF) and (b) submerged downflow (DAF).

Table 3. Mean concentrations of total COD (COD), filtered COD (COD_f), total suspended solids (TSS) and total solids (TS) and the respective removal percentages by the anaerobic filters.

Variables		Affluent	Effluent	
			UAF	DAF
COD	mg L^{-1}	408 ± 186	126 ± 33	75 ± 28
	% Rem.	-	68 ± 15	79 ± 10
COD_f	mg L^{-1}	-	106 ± 23	94 ± 42
	% Rem.	-	68 ± 17	73 ± 15
TSS	mg L^{-1}	132 ± 75	30 ± 22	27 ± 28
	% Rem.	-	73 ± 25	72 ± 29
TS	mg L^{-1}	547 ± 102	392 ± 52	368 ± 49
	% Rem.	-	27 ± 13	32 ± 11

In which: UAF – upflow anaerobic filter; DAF – submerged downflow anaerobic filter. The mean removal efficiencies (% Rem.) of COD, COD_f, TSS and TS did not differ, at 5% probability, by Tukey's test.

Andrade Neto et al. (2001) obtained removal rates of total COD and TSS from 36 to 48% and 45 to 57%, respectively, in the treatment of domestic sewage, using upflow filters filled with size-4 gravel. For downflow filters, the respective removal rates ranged from 42 to 56% and 55 to 61%. Those authors worked with HRT values lower than those applied in this work, ranging between 4.8 and 9.5h.

Comparing all results of organic matter removal between the two filters, it can be observed that they are quite close; this indicates that anaerobic filters can provide equivalent efficiencies, either with upflow or submerged downflow, in the treatment of domestic sewage, as also observed by Andrade Neto et al. (2001). Jawed and Tare (2000) compared upflow and downflow filters in the treatment of synthetic wastewater, and did not find any statistical difference between the removal efficiencies of organic matter between the two filters. However, the mean removal efficiency values were higher for the downflow reactor (estimated at 85%), compared to the upflow filter (estimated at 78%), as observed in this work. Those authors further observed that the distribution of the affluent was more uniform in the upflow filter, and attributed this to the fact that the upflow filter features a uniform clogging process of the false bottom. Sludge deposition on the support medium of the downflow filter was greater and more uneven compared to the other filter. Moreover, larger granules were observed in the downflow filter, with darker coloration (black) – that is, with better quality – when compared to the sludge of the upflow filter, which showed brown-colored granules.

The efficiency values for total COD removal in both filters can be considered satisfactory and close to the variation of COD removal efficiency of 74 to 79% obtained by Manariotis and Grigoropoulos (2006) when treating domestic sewage in UAF with HRT between 0.3 and three days. The authors also observed a 95% TSS removal rate, similar to that observed by Bodkhe (2008) while treating domestic sewage in an anaerobic filter with 0.5 day HRT. Bodkhe (2008) also obtained 95% COD removal under these conditions.

According to Joint Normative Deliberation COPAM/CERH-MG no. 1 of 2008, in order for an effluent to be released into a body of water in the state of Minas Gerais, its COD value should be lower than 180 mg L^{-1}, or rather, the efficiency of the treatment system in reducing COD should be at least equal to 55%, with annual average equal to or greater than 65% (COPAM, 2008). Thus, it can be verified that, with regard to organic matter removal, evaluated by COD, both filters met the requirements of environmental legislation in effect. These results are an indicator that submerged downflow anaerobic filters can be recommended especially when a reduction in construction and operation costs is required, in the primary treatment of domestic effluents that received preliminary treatment.

Fitting the data to the models of organic matter degradation

The values of the parameters of the evaluated models are presented in Table 4. Figure 3 shows the fit curves of the evaluated models, after being fitted to mean experimental COD data. It is observed that the fits obtained in the model used by Brasil et al. (2007) and in the model proposed by Leduy and Zajic (1973) showed the highest coefficient of determination (R^2) values. The model proposed by Brasil et al. (2007) was initially proposed to obtain kinetic parameters of organic matter degradation in wetland systems; nevertheless, its use with data obtained in anaerobic filters proved satisfactory, showing good fit to the experimental data, probably due to the type of flow of the filters. According to Brasil et al. (2007), the first-order model provides an overestimated prediction of organic matter removal, as the obtained mean value for parameter k must remain constant to the distance traveled or the HRT of the wastewater under treatment. The authors affirmed that the reaction constant (k) must decrease with HRT, due to the lower resistance to degradation of a more recalcitrant material that remains in the wastewater. This overestimation of k is evidenced when observing Figure 3, in which the line that describes the first-order reaction is below the data obtained and the lined fitted from the other evaluated models, particularly in the samples taken closer to the exit from filters (HRT = 0.95 and 1.05 day in UAF and DAF). This can also be confirmed when comparing the values of k presented in Table 4.

From the profile analysis of UAF (Figure 3), it was observed that effluent COD concentrations (HRT = 0.80 and 0.95 day) were higher than those obtained in some intermediate collection points, along the length of the anaerobic filter. This result can be indicative of the formation of preferential pathways along the borders of the cross-section of the tubular filter (in the wall/support medium interface) as reported by Bodkhe (2008). A similar performance was observed in DAF (HRT = 0.75 day), although at lower magnitude and differently from that observed by Jawed and Tare (2000). The presence of interstitial sludge proved to be an obstacle to the mixture, resulting in the deposition of a large quantity of suspended solids in the lower part of the upflow anaerobic filter, in which the mixture is poor due to the formation of gas bubbles. Additionally, anaerobic organisms are not uniformly distributed along the height of the filter, resulting in reduced removal efficiency of COD in the upper part of the filter (YU et al., 2006).

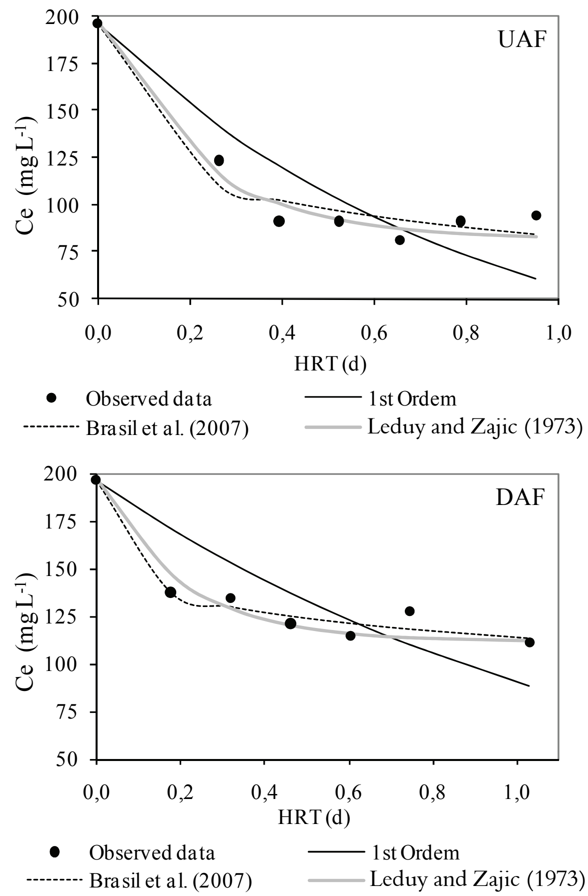

Figure 3. Fit curves of the evaluated models to the experimental COD data.

Table 4. Parameters of the different models of organic matter degradation fitted to the experimental COD data.

Models	Filters	Parameters			
		k	R^2	Cr	N
1st Order	UAF	1.2292±0.1674	0.7091	-	-
	DAF	0.7779±0.1276	0.4561	-	-
Brasil et al. (2007)	UAF	0.8538±0.0863	0.9471	-	0.2987±0.1411
	DAF	0.5435±0.0356	0.9655	-	0.2442±0.0771
Leduy and Zajic (1973)	UAF	4.5611±0.5565	0.9633	81.74	-
	DAF	4.9634±0.7328	0.9390	111.44	-

Despite this tendency to form preferential pathways, the values obtained in this work were higher than those obtained by Padilla-Gasca and López (2010), whose value for the constant of organic matter degradation was 0.70 (20°C) in the treatment of slaughterhouse wastewater in anaerobic filters.

Graaff et al. (2010) cite that the anaerobic degradation coefficient of sewage waters, consisting of feces and urine from domestic sewage, is 0.1 day^{-1}. Teixeira et al. (2008) obtained similar anaerobic degradation constant values of COD for raw and sieved sewage (0.049 day^{-1} and 0.047 day^{-1}, respectively), estimated by the first-order kinetic relationship. In a similar experiment as Teixeira et al. (2008), Elmitwalli et al. (2003) obtained degradation coefficients between 0.15 and 0.30 day^{-1} for organic matter in domestic sewage based on COD – the first value was for 18ºC and the second for 28ºC. The lower values obtained by Teixeira et al. (2008) and Elmitwalli et al. (2003), when compared to those obtained in this work, are likely due to experiment format; those authors incubated domestic sewage and sludge, and the degradation of a single sample was evaluated over time. In continuous-flow anaerobic filters, there was a constant input of organic matter, and as the degradation rate estimated by first-order kinetics is proportional to the concentration of organic matter, lower values were obtained for k (UAF = 1.2292 day^{-1} and DAF = 0.7779 day^{-1}).

Conclusion

According to the obtained data, it can be concluded that:

- the filters provided satisfactory results in removing organic matter, generating effluents with characteristics that meet the requirements set by the environmental legislation in effect in the state of Minas Gerais regarding organic matter measured in the form of COD;
- the removal efficiency of organic matter in the upflow filter was similar to that obtained in the submerged downflow filter;
- the models proposed by Brasil et al. (2007) and Leduy and Zajic (1973) showed the highest coefficients of determination (R^2), with the best fit to the experimental data;
- the first-order kinetic model for removal of organic matter proved less adequate and showed overestimated constant reaction values (k) compared to those obtained using the other models.

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