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Physical-chemical and operational performance of an anaerobic baffled reactor (ABR) treating swine wastewater

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ABSTRACT. Since hog raising concentrates a huge amount of swine manure in small areas, it is considered by the environmental government organizations to be one of the most potentially pollutant activities. Therefore the main objective of this research was to evaluate by operational criteria and removal efficiency, the performance of a Anaerobic Baffled Reactor (ABR), working as a biological pre-treatment of swine culture effluents. The physical-chemical analyses carried out were: total COD, BOD_5, total solids (TS), fix (TFS) and volatiles (TVS), temperature, pH, total Kjeldahl nitrogen, phosphorus, total acidity and alkalinity. The ABR unit worked with an average efficiency of 65.2 and 76.2%, respectively, concerning total COD and BOD_5, with a hydraulic retention time (HRT) about 15 hours. The results for volumetric organic loading rate (VOLR), organic loading rate (OLR) and hydraulic loading rate (HLR) were: 4.46 kg BOD m^{-3} day^{-1}; 1.81 kg BOD_5 kg TVS^{-1} day^{-1} and 1.57 m^3 m^{-3} day^{-1}, respectively. The average efficiency of the whole treatment system for total COD and BOD_5 removal were 66.5 and 77.8%, showing an adequate performance in removing the organic matter from swine wastewater.

Key words: hydrolysis, acidification, efficiency, ABR reactor, UASB reactor.

RESUMO. Desempenho físico-químico e operacional de um reator anaeróbio compartimentado (RAC) como tratamento biológico preliminar de efluentes de suinocultura. A suinocultura por ser uma atividade pecuária concentradora de dejetos em pequenas áreas é considerada, pelos órgãos de gerência ambiental, como uma das atividades mais degradadoras do meio ambiente. Nesta pesquisa objetivou-se, por conseguinte, avaliar a utilização de um reator anaeróbio compartimentado (RAC), como unidade de pré-tratamento de um reator tipo UASB, em escala piloto, na adequação ambiental dos efluentes de suinocultura, avaliando critérios operacionais e a eficiência. As análises físico-químicas realizadas foram: DQO_{total}, DBO_5, sólidos totais (ST), fixos (SF) e voláteis (SV), temperatura, pH, nitrogênio total Kjeldahl, fósforo, acidez total e alcalinidade. A unidade RAC trabalhou com eficiência de 65,2 e 76,2% para a remoção de DQO_{total} e DBO_5, respectivamente, para o TDH médio de 15h. Os valores obtidos para a carga orgânica volumétrica (COV), carga orgânica biológica (COB) e carga hidráulica (CH) foram de 4,46 kgDBO_5 m^{-3} dia^{-1}; 1,81 kg DBO_5 kg SVT^{-1} dia^{-1} e 1,57 m^3 m^{-3} dia^{-1}, respectivamente. O sistema de tratamento proporcionou eficiências médias de remoção de 66,5 e 77,8% para DQO_{total} e DBO_5, respectivamente, demonstrando adequada performance na remoção de material orgânico proveniente do efluente líquido da suinocultura.

Palavras-chave: hidrolização, acidificação, eficiência, RAC, UASB.

Introduction

Hog raising is a livestock raising activity that generates dejects and mostly uses small areas. The production and accumulation of large quantities of hog raising residues make this activity potentially pollutant for the soil, water and air (PEREIRA et al., 2010).

In recent decades, interest in knowledge of the anaerobic digestion process has grown considerably in Brazil. This process of stabilizing organic matter has been shown to be suitable for the tropical climate conditions and has shown a favorable energetic balance in relation to the aerobic technologies, due to products such as biogas, biofertilizers (sludge and fertirrigation) and also low operational energy demand. Anaerobic reactors are used in this process and consist of an active biomass that digests the biodegradable substrates and transforms them into other by-products (CAMPOS et al., 2010).

The application of anaerobic process for treating residues, using high rate reactors, solved many problems for wastewaters with high BOD_5

(LOURENÇO; CAMPOS, 2009). The microorganisms physically organized in bacterial agglomerates, as biological granules or pellets are easily retained within the system, resulting in long cell retention regardless of the hydraulic retention time (FERNANDES; OLIVEIRA, 2006).

Considering hydrolysis as a limiting step in anaerobic degradation of complex residues such as wastewater originated from swine culture, the anaerobic treatment systems widely proposed for these effluents comprise two different stages. The system was composed by two different reactors working in series, where the first one aimed at carrying out a partial hydrolysis of particulate organic matter (pre-treatment) and the other the stabilization of soluble compounds synthesized in the former reactor, end up by producing methane.

The utilization of two stages in the anaerobic process is due to the high concentration of organic matter especially in these wastewaters, without which it would negatively interfere in the microorganisms activity, and consequently in the development and maintenance of sludge granulation (LETTINGA; HULSHOFF-POL, 1991).

The Anaerobic Baffled Reactor (ABR) is highly efficient in retaining the particulate organic fraction (BOOPATHY, 1998), and also can contribute to the removal of organic material in the treatment systems. It has good shock load absorption whether organic or hydraulic, low sludge production, longer biomass retention time and also helps the hydrolysis and digestion of soluble solid compounds. The most significant advantage of the ABR is the capacity for hydrolyzing and acidifying, making the liquid effluent suitable thus permitting those specific groups of bacteria act under favorable conditions for methanification (BARBER; STUCKEY, 2000).

The ABR is the result of the UASB (Upflow Anaerobic Sludge Blanket Reactor) modifications and consists of several vertical chicanes that force the affluent wastewater move upwards, passing through dense layers of bacteria populations present in the sludge blanket in each one of the compartments. This artifice enables greater contact between the affluent and the microorganisms disposed in series and confers greater yields for organic compound degradation in addition to a hindering the loss of solids by dragging. The ABR used in this present research has three compartments in series, where the biogas production is accumulated in each one of the compartments independently.

The main objective of this study was to investigate the use of the ABR as pre-treatment of swine wastewater applying operational criteria that could influence the efficiency of the referred unit.

Material and methods

The pilot treatment system was set in the hog raising sector at the Department of Animal Science (DZO) at the Federal University of Lavras (UFLA). The physical and chemical analyses (Table 1) were carried out in the Water Analysis Laboratory (LAADEG), in the Water and Soil Sector of the Engineering Department of UFLA. The treatment units that comprised the operational system were: sand retention box (SRB), curved profile static sieve (SS), acidification and equalization tank (AET), anaerobic baffle reactor (ABR) and an upflow anaerobic sludge blanket reactor (UASB).

Table 1. Physical-chemical parameter, methodology and the respective monitoring frequency.

Physical and chemical Parameters	Frequency	References
pH	Fortnightly	APHA, AWWA, WPCF (1998)
Total, partial and intermediate Alkalinity	Fortnightly	Chernicharo (2007)
Chemical Oxygen Demand (Total COD)	Fortnightly	APHA, AWWA, WPCF (1998)
Biochemical Oxygen Demand ($BOD_5^{20°C}$)	Weekly	Wincley methodology
Total Fixed and Volatile Solids	Weekly	APHA, AWWA, WPCF (1998)
Total Kjeldahl Nitrogen (TKN)	Fortnightly	APHA, AWWA, WPCF (1998)
Total Phosphorus (Total- P)	Fortnightly	APHA, AWWA, WPCF (1998)
Total Acidity	Fortnightly	Methods of pH meter using NaOH 0,02 N
Electrical Conductivity	Fortnightly	Conductivity
Oils and Grease	Fortnightly	APHA, AWWA, WPCF (1998)

The SRB had the objective of retaining abrasive materials and was constructed in the following dimensions: 2.20 m long, 0.53 m wide. The affluent flow was measured by a triangular spillway (Thompson) measuring 9.5 cm at the base and 9.5 cm high. After passing through the SRB the affluent was taken to the SS that has a stainless steel 1.180 mm long mesh. The steel support components were of trapezoidal shape and with 2.5 mm mesh. The steel support had a trapezoidal form of 1.5 x 0.7 mm. The SS was fed through the top were the liquid part was then taken over the SS surface, where most of the solids were retained, and the liquid entered the PVC box through the meshes structure. The affluent after passing through the sieve was directed to a 8.5 m^3 steel/carbon tank called the acidification and equalization tank (AET), and then pumped to the treatment system by a Nemo type Netzsch pump with a positive displacement stator. The pumping was controlled by a 12 entry WEG-CFW08 frequency inverter that allowed precise adjustment of the flow and therefore the load applied to the system could be accurately modified. The pump was kept at 1,600 rpm rotation and the flow was measured every day by the gravimetric method using a 1-liter plastic test tube (J. Prolab).

The three compartments of the ABR, C1, C2 and C3, had the respectively volumes of 1.72, 2.12 and 2.24 m^3. The areas corresponding to each compartment were 0.638, 0.787 and 0.832 m^2. This reactor was built of bricks with extra strong mortar and covered inside with an asphalt blanket and later on waterproofed with fiberglass to further increase the impermeability.

The output flow in each compartment was equalized by leveled fiberglass conductor pipes with various triangular spillways (Thompson) so there was a homogeneous flow in each one of the compartments. The sludge profile was probed using four PVC registers, T1, T2, T3 and T4, installed in each compartment that were numbered from the bottom to top.

A Digital Thermo-Hygrometer was installed in the side of the ABR in order to control the maximum, minimum and average temperatures, as well as the moisture measurements. Readings were taken daily at about 8 a.m. and, after each reading, the apparatus was reasserted again. The sludge temperature was measured by a mercury thermometer (Inconterm L-191/07).

Startup

The system was started up without biomass inoculation, using sedimentation parameters (COSTA, 2009). At the start of this research the sludge in the BAR compartments were leveled to the last recording (T_4) at 1.75 m from the bottom of the reactor. After the startup, the exceeding sludge was removed every five days to control the sludge quantity, this procedure was carried out in all the ABR compartments.

Theoretical biogas production

The theoretical biogas production was determined in function of the organic load applied to the reactor (flow versus total COD concentration). A standard value was adopted for the specific methane production (0.35 m^3 CH_4 per kg total COD removed, in the CNTP) (CAMPOS et al., 2005). The biogas volume for the local temperature and pressure conditions was corrected by the equations 1, 2 and 3, below:

$$P = P_0 \text{ x } e^{\frac{-Mgz}{RT}} \qquad (1)$$

where:

P = corrected pressure (atm);

P_0 = atmospheric pressure at sea level (1 atm);

M = mean molar mass of the air (0.0289 kg mol^{-1});

g = gravitation constant (9.806m s^{-2});

z = local altitude (m), (Lavras 885m);

R = gas constant $(8,31 \frac{\text{Pa m}^3}{\text{mol K}})$;

T = temperature (K), the reactor operated at a mean temperature of 22.8°C = 295.8 K.

According to data detected in the ABR Reactor:

$$K(t) = \frac{P \text{ x } K}{R \text{ x } (t + 273)} \qquad (2)$$

where:

K(t) = correction factor of the reactor operating temperature (g COD L^{-1});

P = local atmospheric pressure (atm);

K = total COD_5 corresponding to one mol CH_4 (64 g COD mol^{-1});

R = gas constant $(8,31 \frac{\text{Pa m}^3}{\text{mol K}})$;

t = reactor operating temperature (°C).

$$V_{CH_4} = \frac{\text{total } COD_{CH_4}}{K(t)} \qquad (3)$$

where:

VCH_4 = methane volume produced (L);

$CODCH_4$ = COD removed from the reactor and converted to CH_4(g COD), that is, ($COD_{mean\ removed}$) x flow (Q_{mean});

K(t) = correction factor of the reactor operating temperature (g COD L^{-1}).

Results and discussion

Climatic factors

The local temperature average was 21°C, minimum and maximum temperatures ranging from 16 to 28°C. The humidity average was 75% at the time of the collections, and the minimum and maximum was 31 and 96%, respectively.

The ABR operated with average temperature of 24°C, especially for the sludge temperature, and mean temperature of 22°C for the effluent.

According to Mahmoud et al. (2003), the velocity conversion of complex organic matter is limited by hydrolysis stage. The velocity of hydrolysis is highly dependent on temperature, since it is known that, the process (hydrolysis) is a chemical reaction catalyzed by enzymes, which are very sensible to temperature oscillations. The operational temperature of a reactor has a substantial effect in organic matter conversion, therefore, affecting the sludge characteristics. As the ABR has operated within mesophilic range temperature, namely from 20 to 30ºC, and yet, within the spring and summer temperatures, it has been accepted that the reactor has operated in the optimum temperature range enabling a good performance. Santana and Oliveira (2005), quote the mesophilic range as appropriate for biological anaerobic degradation processes of organic matter, although the average temperature is below the range quoted by Chernicharo (2007).

The affluent flow, obtained from the sand retention box (SRB), was measured throughout the day from 7:30 a.m. to 4:30 p.m., in a total of 11 daily measurements and varied greatly. These flow variations were due to the washing the stalls and reached peaks of up to 8.72 L s^{-1}.

Hydraulic Retention Time (HRT)

After startup, the ABR worked under steady-state conditions with the pump in constant rotation until the end of the experiment. However, even with the pump in constant rotation there were variations in flow due to the head loss in the piping lines, influenced by the solids that varied the concentration and consequently its viscosity, producing small variations of HRT.

Table 2 shows that the HRT ranged from 13 and 20 hours, thus the HRT calculated to represent the mean values for the C_1, C_2 and C_3 compartments were: 6.0, 5.0 and 5.0 hours, respectively.

Hydraulic Loading Rate (HLR)

The initial HLR applied to the ABR compartments were: 3.42, 3.74 and 3.92 m^3 m^{-3} day^{-1} for C_1, C_2 and C_3, respectively. Gradually the HLR increased during the research to 4.94, 5.39 and 5.65 m^3 m^{-3} day^{-1} for C_1, C_2 and C_3, respectively. If compared with the same values of Table 2, it is possible to observe that the variation of the HLR in each container, in relation to the total volume of the unit were different. It may be deduced that in designing this type of reactor it is important to calculate each chamber individually.

Volumetric Organic Loading Rate (VOLR)

The literature reports extremely high VOLR applied successfully in pilot installations for the treatment of human wastewater, up to 45 kg COD m^{-3} day^{-1} (CHERNICHARO, 2007), although the volumetric organic loads adopted in small-scale station projects have been lower than 15 kg COD m^{-3} day^{-1}. According to the same author, the VOLR can be used to determine the reactor volume. Table 2 shows that the VOLR applied to the ABR ranged from 3.53 and 5.10 kg BOD_5 m^{-3} day^{-1} with an average value of approximately 5.11 kg BOD_5 m^{-3} day^{-1}.

Biological Organic Loading Rate (BOLR)

The biological organic loading rate (BOLR) reports the organic load in terms of BOD_5, applied to the biomass present in the reactor, whose mean values in each one of the three compartments were 1.72, 1.67 and 1.55 kg BOD_5 kg VTS^{-1} day^{-1} for C_1, C_2 and C_3, respectively.

Ascentional velocity (AV)

The maximum ascentional velocity (AV) in the reactor depends on the sludge capability and the loadings applied. For reactors operating with flocculent sludge and organic loading about 5 to 6 kg COD m^{-3} day^{-1}, the average of AV can reach up to 0.5 a 0.7 m h^{-1}, and temporary picks can be tolerate during 2 to 4 hours, with velocity ranging from 1.5 a 2.0 m h^{-1}. When sludge is in granular form, the ascentional velocities can be expressively larger, up to 10 m h^{-1} (CHERNICHARO, 2007)

It can be observed that the ascentional velocities of each compartment presented within excellent interval for flocculent sludge, as shown in Table 2.

Table 2. Operational and hydraulic performance of anaerobic baffled reactor (ABR).

	HLR	VLR	HRT	AVC1	AVC2	AVC3
Average	1.57	4.52	15.38	0.58	0.47	0.44
Minimum	1.23	3.53	13.50	0.45	0.37	0.35
Maximum	1.78	5.11	19.50	0.72	0.58	0.55
VC	0.09	0.09	0.10	0.13	0.13	0.13
Median	1.60	4.62	15.00	0.56	0.45	0.43
Geometric average	1.57	4.50	15.31	0.57	0.46	0.44
Variation						
Stander Deviation	0.14	0.40	1.48	0.08	0.06	0.06
Aver. - 1 sd	1.43	4.11	13.90	0.50	0.41	0.38
Aver.+ 1 sd	1.71	4.92	16.85	0.65	0.53	0.50

HLR (m^3 m^{-3} day^{-1}); VLR (kg $BOD_5^{20°C}$ m^{-3} day^{-1}); HRT (hours); AVC1, 2, 3- Ascentional velocity in the chamber 1, 2, 3 (m h^{-1}).

ABR physical-chemical efficiency

According to (CHERNICHARO, 2007), the most important point, regarding to the pH value and its stability, is to know if the alkalinity within reactor is enough to buffering itself in safe ranges. In operational perspective, if the alkalinity is generated from the influent wastewater, it is advisable to maintain the high value of the alkalinity in the reactor in order to favor the buffering effect for high quantity of acids within the reactor. It is important to outline that, the minimum acceptable quantity of alkalinity depends on the wastewater concentration.

As the concentration of swine wastewater was high, it was observed the generation of bicarbonate alkalinity in the effluent, contrary to the reactor influent (Figures 1 and 2), helped the buffering capacity of the reactor. As the alkalinity increased through the partial Alkalinity, without considerable contribution of intermediate alkalinity, it was observed that the IA/PA decreased roughly from 1.9 to 1.6.

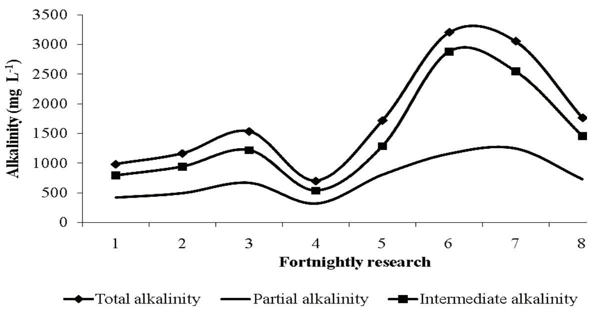

Figure 1. The alkalinity behavior in the influent of ABR.

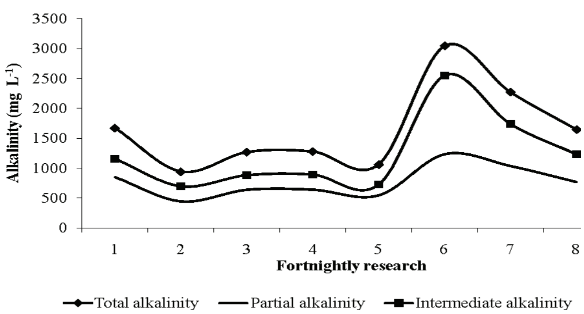

Figure 2. The alkalinity behavoir in the effluent of ABR.

According to Pereira et al. (2009) a system with a small variation in pH shows a good buffering capacity that could be defined as the capacity of a solution to prevent sudden changes in pH.

The following results were obtained in 120 days of experiment in the treatment system: pH means for the sand retention box, static sieve, AET and ABR effluent were 8.15, 8.02, 7.25 and 7.12, respectively. There was a 1.03 fall in the pH in the influent of the ABR unit that helped the acidification process in the AET, responsible for hydrolyzing and acidifying of the effluent in order to easy the bacteria methanogenic action through a pH values between 6.0 and 8.0 (Table 3).

Table 3. Physical and chemical performance of the influent of the ABR.

Parameters	pH	T Ac.	EC	TS	FS	VS	TNK	P	OG
Average	7.1	30.5	3.7	2720.9	1077.4	1647.8	53.9	1.1	396.6
Minimum	6.9	10.1	2.9	1513.3	770.0	731.7	32.0	0.7	68.5
Maximum	7.5	86.6	4.3	4030.0	1695.0	2361.0	118.1	1.4	880.0
VC	0.0	0.7	0.1	0.3	0.3	0.4	0.5	0.2	0.7
Median	7.1	21.4	3.7	2760.5	1057.9	1704.7	44.2	1.1	396.6
Geometric average	7.1	25.2	3.6	2572.6	1042.9	1518.3	49.4	1.0	291.3
Variation									
Standard deviation	0.2	22.3	0.5	935.0	307.3	656.9	29.1	0,2	293.0
Aver- 1 sd	6.9	8.2	3.2	1785.9	770.1	990.9	24.8	0,8	103.6
Aver + 1 sd	7.3	52.8	4.1	3656.0	1384.7	2304.6	83.0	1,3	689.6

Ac.T, TS, FS, VS, TNK, P, OG-concentration (mg L^{-1}), EC (dS cm^{-1}).

The mean acidity in the ABR was 35.8 and 30.5 mg L^{-1} in the influent and effluent, respectively, and a mean value of 25.9 mg L^{-1} was observed for the whole treatment system (Tables 3 and 4).

Table 4. Physical and chemical performance of the affluent of the ABR.

Parameters	pH	T Ac.	EC	TS	FS	VS	TNK	P	OG
Average	7.25	35.76	3.77	3789.29	1150.29	2639.00	50.67	1.50	345.17
Minimum	6.97	15.29	1.89	2660.00	791.67	1868.33	32.00	0.70	32.00
Maximum	7.81	94.65	5.53	5615.00	1698.33	3916.67	105.90	2.46	930.50
VC	0.04	0.74	0.25	0.23	0.27	0.24	0.51	0.36	0.83
Median	7.17	23.66	3.70	3792.98	1066.67	2662.17	37.80	1.50	345.17
Geometric average	7.25	29.11	3.65	3706.63	1116.01	2579.63	46.67	1.41	239.80
Variation									
Standard deviation	0.28	26.49	0.95	877.32	312.55	622.07	25.68	0.54	287.27
Aver - 1 sd	6.97	9.27	2.83	2911.96	837.73	2016.93	24.99	0.96	57.89
Aver + 1 sd	7.53	62.26	4.72	4666.61	1462.84	3261.07	76.34	2.04	632.44

Total acidity (TA), total solids (TS), Fixed solids (FS), VS=Volatile Solids, TNK, P, OG= Oils and Grease (OG) concentration (mg L^{-1}), EC (dS cm^{-1}).

Mean values were observed in the influent and the affluent of the ABR unit of 3.067 and 684 mg L^{-1} for BOD_5; and 8.057 and 2.703 mg L^{-1} for COD_{total}, respectively. There was little variation in the removal to the static sieve (Table 5) due to the short retention time in that unit. A decrease was observed after AET for the BOD_5 and the COD_{total}, due to decantation and digestion of the solids formed in the settled sludge that helped the bacterial activity, especially hydrolysis and the acid generating bacteria.

The Table 5 shows the variation in the system efficiency and in the ABR unit that were mainly due to the changes in temperature, deject dilution, rainfall and pig feeding; these changes were expected when working in a pilot agroindustrial station constructed in the countryside. The mean efficiencies for the ABR and for the system regarding BOD_5 removal were 76.2 and 77.7%, while for COD_{total} removal were 65.2 and 66.4%, respectively.

Table 5. Variations in the system efficiency and the ABR.

Parameters	BOD	COD	EF % (BOD)	EF % (COD)
Average	675.49	7773.33	74.0	67.5
Minimum	292.19	1916.67	60.7	41.9
Maximum	1076.35	17133.33	87.3	84.1
VC	0.38	0.66	0.11	0.18
Median	675.49	7266.67	75.3	70.2
Geometric average	628.31	6367.49	73.6	66.4
Variation				
Standard deviation	254.87	5139.22	8.08	12.01
Aver - 1 sd	420.62	2634.11	65.9	55.5
Aver+ 1 sd	930.36	12912.56	82.1	79.5

Campos et al. (2004) considered that the N, P and K concentration in animal manure was related to the quality of the food consumed and the size of the animal in function of live weight. They further observed that large total nitrogen concentrations, both in the ABR and in the effluent negative removal values (Table 3) were due to the solids wash-out.

The phosphorus values detected may represent high risk and cause eutrophication since after treatment the values greatly surpassed the limit ($p < 0.05$ mg L^{-1}) for release in lentic hydric bodies and environment in general, according to Conama (2005) (Table 3).

The oil and grease concentrations in the system were little greater in the influent because there was accumulation by flotation, so when the scum flakes in the effluent were collected, a negative removal efficiency resulted.

It can be stated that the effluent of the system was outside the standards according to the laws proposed by Conama (2005), Tables 3 and 4.

Theoretical biogas production

According to the calculations reported previously used by Campos et al. (2005), produced biogas volumes were observed ranging from 10 L day^{-1} to 47 L day^{-1} representing a daily average production of 27 L day^{-1}.

It was expected that the biogas production would be small due to the ABR reactor pretreatment. As stated previously, the ABR reactor was linked to a measuring and biogas burning system, so that all the biogas produced was recorded by the gasmeter. However, it was recorded very few amount of biogas, since the biogas escaped, due to leakage problems, through the upper part of the unit to the atmosphere.

Conclusion

In the Anaerobic Baffled Reactor (ABR) we tried to provide adequate conditions for the first step of the anaerobic reactions such as hydrolysis, acidification and acclimatization of the substrate with the sludge, and therefore, the methanogenesis process could be facilitated in the later unit (UASB).

The current environmental legislation determines that for releasing the liquid effluent in water bodies, the BOD5 should be at least 60 mg L^{-1}, whose limit can only be surpassed, if the efficiency of the treatment system is greater than 80% in terms of BOD_5 reduction, and further, when the effluent released does not alter the quality or the standards classification by which the waterbodies is registered (VON SPERLING, 2006). Thus we concluded that the ABR alone did not meet the legislation and post-treatment was required.

The use of the anaerobic process in two stages, with the ABR and UASB reactors acting in series, may perform better the organic solids removal, increasing hydrolysis in the first reactor and improving organic matter removal and methane production in the second one, thus conferring greater stability to the treatment system. The major part of the organic matter removal, suspended solids, and macro-micronutrients occurred in the ABR reactor, mostly in the first chamber.

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