POSTCOSECHA: BIOLOGÍA Y TÉCNOLOGÍA
POSTHARVEST: BIOLOGY AND TECHNOLOGY

ARTÍCULO ORIGINAL

Performance of a UASB reactor treating coffee wet wastewater

Digestión anaerobia, aguas residuales de café, reactor UASB

Dr.C. Yans Guardia Puebla[I], Dr.C. Suyén Rodríguez Pérez[II], M.Sc. Janet Jiménez Hernández[III], Dr. Víctor Sánchez Girón[IV]

[I] Universidad de Granma (UDG), Departamento de Ciencias Técnicas, Bayamo, Cuba.
[II] Universidad de Oriente (UO), Centro de Estudios de Biotecnología Industrial (CEBI), Santiago de Cuba.
[III] Universidad de Sancti Spíritus, Centro de Estudios de Energía y Procesos Industriales, Sancti Spíritus, Cuba.
[IV] Universidad Politécnica de Madrid (UPM), Escuela Técnica Superior de Ingenieros Agrónomos (ETSIA), Madrid, España.

ABSTRACT. The present work shows the results obtained in the anaerobic digestion process of coffee wet wastewater processing. An UASB anaerobic reactor was operated in single-stage in mesophilic temperature controlled conditions (37±1ºC). The effect of both organic loading rate (OLR) and hydraulic retention time (HRT) in the anaerobic digestion of coffee wet wastewater was investigated. The OLR values considered in the single-stage UASB reactor varied in a range of 3,6-4,1 kgCOD m^{-3} d^{-1} and the HRT stayed in a range of 21,5-15,5 hours. The evaluation results show that the best performance of UASB reactor in single-stage was obtained at OLR of 3,6 kg COD m^{-3} d^{-1} with an average value of total and soluble COD removal of 77,2% and 83,4%, respectively, and average methane concentration in biogas of 61%. The present study suggests that the anaerobic digestion is suitable to treating coffee wet wastewater.

Keywords: residual treatment of water, anaerobic reactor.

RESUMEN. El siguiente trabajo muestra los resultados alcanzados en el proceso de digestión anaerobia de las aguas residuales del beneficiado húmedo de café. Un reactor anaerobio UASB fue operado en una etapa en condiciones controladas de temperatura mesofílica (37±1ºC). Se investigó el efecto de la carga orgánica volumétrica (COV) y el tiempo de retención hidráulico (TRH) sobre el proceso de digestión anaerobia de las aguas residuales del beneficiado húmedo de café. Los valores de COV considerados en el sistema UASB en una etapa variaron en un intervalo de 3,6-4,1 kgCOD m^{-3} d^{-1} y los de TRH estuvieron en un intervalo de 21,1-15,5 horas. Los resultados de la valuación mostraron que el mejor funcionamiento fue alcanzado a una COV de 3,6 kg COD m^{-3} d^{-1} con un valor promedio de eficiencia de eliminación de DQO total y soluble de 77,2% and 83,4%, respectivamente, y un concentración de metano en el biogás de 61%. El actual estudio demuestra que la digestión anaerobia es adecuada para tratar las aguas residuales del beneficiado húmedo de café.

Palabras clave: tratamiento de aguas residuales, reactor anaeróbico

INTRODUCTION

World coffee production reached the Figure of 7 900 000 tons in 2010 and it is major economic activity in several tropical countries. The coffee bean, which is the portion of the cherry useful for human consumption, represents 20% of the total volume of the cherry. The bean extraction process is called in Latin America “Beneficio”, and generates waste accounting for 80% of total raw volume processed (Orozco *et al.,* 2005). There are two types of processing: dry and wet. Wet processing is the most widely used treatment method in coffee producing countries. The method emerged as an alternative to solve the problem of rapid and excessive fermentation of the cherries in tropical regions. After the harvest, the external components of the cherry are removed and the beans are placed in fermentation tanks to release the mucilage by hydrolysis. The process consumes large amounts of water that are sometimes poured without any adequate treatment to the surface waters. This situation causes a significant environmental impact since these wastewaters have high organic contamination ranging from 2400 to 21900 mgCOD L^{-1}, large amount of suspended solids, and their turbidity results in unpleasant odors and in a loss of visual quality (Bello-Mendoza and Castillo-Rivera, 1998, Houbron *et al.,* 2003, Narasimba *et al.,* 2004, Devi *et al.*, 2008, Selvamurugan *et al.*, 2010a, Fia *et al.*, 2012). Since coffee wastewaters have high carbohydrate concentration biological processes, either aerobic or anaerobic digestion, are suitable for their treatment.

Anaerobic treatment has some advantages over conventional aerobic treatment such as: greater removal efficiency of the chemical oxygen demand (COD), reduced sludge production, low power consumption, reduced space requirements, a relatively simple construction, low nutrient requirements and generation of a gas with a high calorific power (methane). However, some other aspects like long start-up, low nutrient and pathogen removal, possible generation of odors and the need for a post-treatment have had a negative impact on the implementation of the anaerobic process (Ward *et al.*, 2008).

High-rate anaerobic reactors have the ability to handle high organic loading rates (OLR), high up-flow velocities, and low hydraulic retention times (HRT). Therefore, a reactor of smaller volume is required even to produce large amounts of biogas. Upflow anaerobic sludge blanket (UASB) reactor and the upflow anaerobic filter (UAF) reactor are examples of high-rate reactors that have been used in the treatment of several types of wastewater.

Some experiments conducted with several types of coffee wastewaters have faced difficulties in obtaining a stable performance of the anaerobic digestion due to the acidity and low alkalinity of these wastewaters, and the presence in the latter of the inhibitory compounds of the process (Hajipakkos, 1992, Fernández and Foster, 1993, Dinsdale *et al.*, 1997a, Dinsdale *et al.*, 1996, Dinsdale *et al.*, 1997b, Neves *et al.*, 2006, Guardia-Puebla *et al.*, 2010). Furthermore, the coffee wet wastewaters have large amounts of organic matter of easy hydrolysis that causes a high VFA production. An accumulation of VFA in the reactor affects negatively the methanogenic bacteria due to a pH drop (Bouallagui *et al.,* 2004).

The literature suggests that the anaerobic digestion of the coffee wet wastewaters is possible. The main aim of this study was to evaluate the potential of a UASB reactor treating coffee wet wastewaters. The behavior of UASB system was assessed considering five variables: total and soluble COD removal efficiencies, VFA concentration, biogas production and methane concentration.

METHODS

Reactor

Figure 1 shows a scheme of the configurations of the laboratory scale anaerobic system that were used, which consisted of a UASB reactor. The reactor was kept at mesophilic temperature (37±1ºC) in a constant-temperature room. UASB system consisted on a glass cylindrical reactor of 0,40 m of height and 0.09 m of diameter, with a nominal volume of 2,5 L. It was equipped with a Masterflex® L/S® variable-speed modular drive (model HV-07553-75, 6-600 rpm), which provided a variable flow for the for the residual income and the effluent recycle.

Feed and seed

The inoculum used was granular sludge coming from an industrial scale UASB reactor that processed canned juice wastewaters having a volatile suspended solid (VSS) concentration of 73,5 g L^{-1}. The laboratory reactor was fed with coffee wet processing wastewater, located in Ixhuatlán community, Veracruz, Mexico. The composition of the wastewater is shown in Table 1. As the coffee wet processing wastewater was acid its pH had to be adjusted using sodium bicarbonate ($NaHCO_3$).

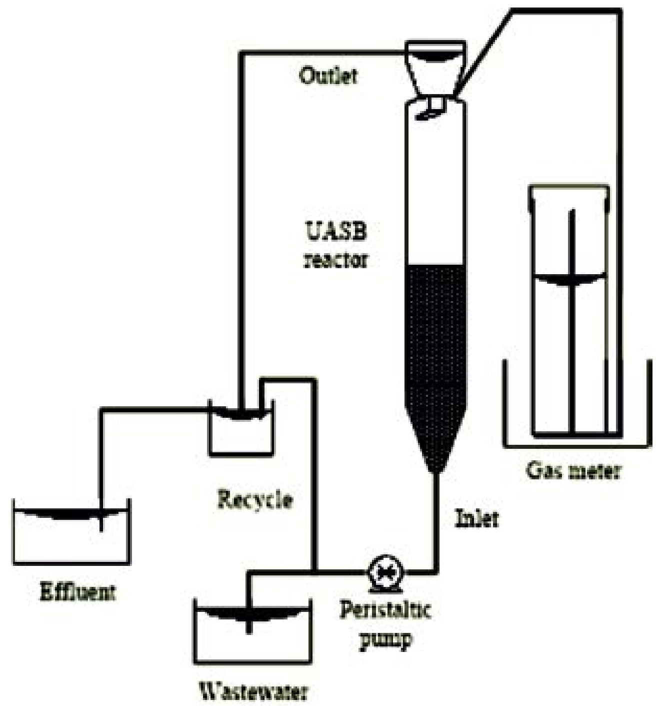

FIGURE 1. Experimental setup of the UASB system.

Experimental procedure

UASB system was inoculated with 0,4 L of granular sludge. The start-up procedure was carried out by the OLR gradual rise, increasing weekly the COD concentration from influent until the evaluation conditions. This process was continuously carried out for four weeks. The system evaluation was analyzed when the start-up of the reactor finished. Pseudo-steady-state condition was considered attained when finished the week four. The OLR was subsequently step increased to the next higher rate through shortening of HRT. The OLR evaluated in each system (calls Run1, Run2 and Run3) are detailed in Table 2. The evaluation periods from each OLR used were three weeks. The recycle internal rate (recycle of the effluent to the inlet stream) applied to the UASB in a stage throughout the period of experimentation was 1,0.

TABLE 1. Characteristics of the coffee wet wastewater

Parameters	Wastewater
Total COD (mg L^{-1})	2545±142 (60)
Soluble COD (mg L^{-1})	2302±175 (60)
pH	3,79±0,21 (60)
ST (mg L^{-1})	1228,5
TVS (mg L^{-1})	1141,6
SST (mg L^{-1})	315,7
SSV (mg L^{-1})	271,2

TABLE 2. Operating parameters of UASB system

System	Parameters	Run1	Run2	Run3
UASB	HRT total (h)	21,5	18,5	15,5
	Flow (L h^{-1})	0,15	0,16	0,17
	OLR (kg COD m^{-3} d^{-1})	3,6±0,1 (15)	3,8±0,2 (15)	4,1±0,1 (15)
	Recycle rate	1,0	1,0	1,0

Analytical methods

Total suspended solids (TSS), volatile suspended solids (VSS), pH and alkalinity were determined according to the Standard Methods for the Examination of Water and Wastewater (APHA, 1995). The alpha index was calculated as the quotient of partial alkalinity at pH 5,75 and total alkalinity at pH 4,30. Total and soluble chemical oxygen demand (COD) analyses were carried out using a HACH COD reactor (digestion at 150°C for 2 h) according to the closed reflux colorimetric method described in Standard Methods for the Examination of Water and Wastewater (APHA, 1995).

Volatile Fatty Acids (VFA) were analyzed with a gas chromatograph (Chromatograph SRI 8610 model, with a flame detector, Zebron column, and Helium gas carrier to 30 psi). Two millilitres samples were taken from the reactor with a syringe and deposited in the Eppendorf tube, and two drops of hydrochlorate acid were added (solution 1:1). The samples were centrifuged by half an hour at a 3500 rpm in a micro-centrifuge Eppendorf. The supernatant were filtered through Wathman paper (0,22 µm), and conserved at 4°C until being used.

The biogas production was daily quantified by displacement of the liquid column placed in each of the reactors gas meters. The methane concentration in biogas was measured by gas chromatography (Chromatograph Fisher Gas Partitioner Model 1200, equipped with a detector of thermal conductivity, double column Porapack Q and mesh molecular SA, with Helium gas carrier flow of 25 mL min^{-1}). Molar fractions of methane from analyzed samples were determined by comparing the peak areas of the component with pure methane.

RESULTS AND DISCUSSION

pH and alpha index

The pH behavior observed during the evaluation period of the UASB reactor can be seen in Figure 2a. When the inflow wastewater pH was adjusted at 7,0, the UASB reactor showed a stable performance, with a pH interval of 7,8-8,4 and an average value of 8,1±0,15. Occurrence of the anaerobic digestion requires a pH interval of 6,5-8,2 (Speece, 1996). Values of this parameter below 6,5 favor acidification, especially in this type of wastewater with pH values <4,0. This fact inhibits the methanogenic population and, therefore, the efficiency of the anaerobic treatment is reduced. Considering the alkaline values of the effluent and the cost incurred in the neutralization of the wastewater with sodium bicarbonate, a pH adjustment to a value of 6,5 was done in the wastewater to treat from day 64 onwards (i.e. in the course of Run 2). These new conditions favored pH values of the effluent in the interval 6,5-7,1, with an average value of 6,9±0,2, until the end of the experiment. Given the characteristics of this coffee wastewater, and even though the pH values stayed within in the appropriate interval, it is recommendable, in order to prevent possible destabilizations in the reactor, to reach values of the pH near to those measured in Run1, which were obtained after adjusting to pH 7,0 the wastewater to treat.

An aspect related to pH is alkalinity, where the alpha index indicates the absorbing capacity of the system to any abrupt pH change in the reactor. In this study a quick increase in the alkalinity from 1612 and 2192 mg$CaCO_3$ L^{-1} was observed in the start-up stage. A similar behavior was observed when the pH in the inflow wastewater was kept constant and equal to 7,0, with an alkalinity average value of 1935±128 mg$CaCO_3$ L^{-1}. Therefore, pH increases above the optimal interval were observed although the wastewater to treat had been neutralized. When the pH was readjusted to 6,5, the alkalinity decreased to a value of 1355±67 mg-$CaCO_3$ L^{-1}. Whenever the pH value of the wastewater was 7,0 and its average alkalinity 1935±128 mg$CaCO_3$ L^{-1}, the reactor behavior was similar to that observed in the start-up stage. Similarly, this so high value of the alkalinity favored increases of the pH above the optimal interval even though the wastewater to be treated had been neutralized.

Some authors have suggested that the larger the alpha index value the better the buffering capacity of the system. Jenkins *et al.* (1983), recommended that the alpha index values should be larger than 0,5. As a rule of thumb, this figure shows a good performance of the reactor. As it can be seen in Figure 2b, the alpha index reached an average value very close to the optimal, 0,51±0,02, after the first week of the start-up stage. However, when the pH in the inflow was adjusted to 6,5 the average alpha value decreased to 0,48±0,02. This decrease in the alpha value with the pH is associated to an accumulation of acid species in the reactor that could cause system instability. pH is not a sensitive indicator, since it could conceal the increase of the H^+ concentration even though it could show suitable values. Therefore, to carry out a continuous monitoring of an anaerobic processes, and even to make decisions, the alpha index is a better option (Pérez & Torres, 2008).

One of the main problems of the anaerobic biological degradation of this type of wastewater is the high content of easily fermentable organic matter. Organic matter compounds cause a fast acidification of the wastewater that results in a high production of VFA & therefore, it is necessary the addition of an alkaline substance to increase the pH. In order to prevent the accumulation of VFA, it is advisable to recycle the treated effluent with the aim of re-use the alkalinity of the anaerobic process to reduce the consumption alkaline substances (Romli et al., 1994). In addition, the recycle can be used to maintain a suitable hydraulic load in the anaerobic reactors when high concentrated wastewaters are being treated (Lier, 2008).

VFA concentration

Total VFA concentration was considered as the sum of the acetic, propionic and butyric acids concentrations. It was observed a tendency to increase VFA concentrations in the effluent with increasing OLR values (Figure 2c). In an overloaded anaerobic system it can be observed an accumulation of VFA because the methanogenic bacteria can not remove the hydrogen and VFA produced (Nagao *et al.*, 2012).

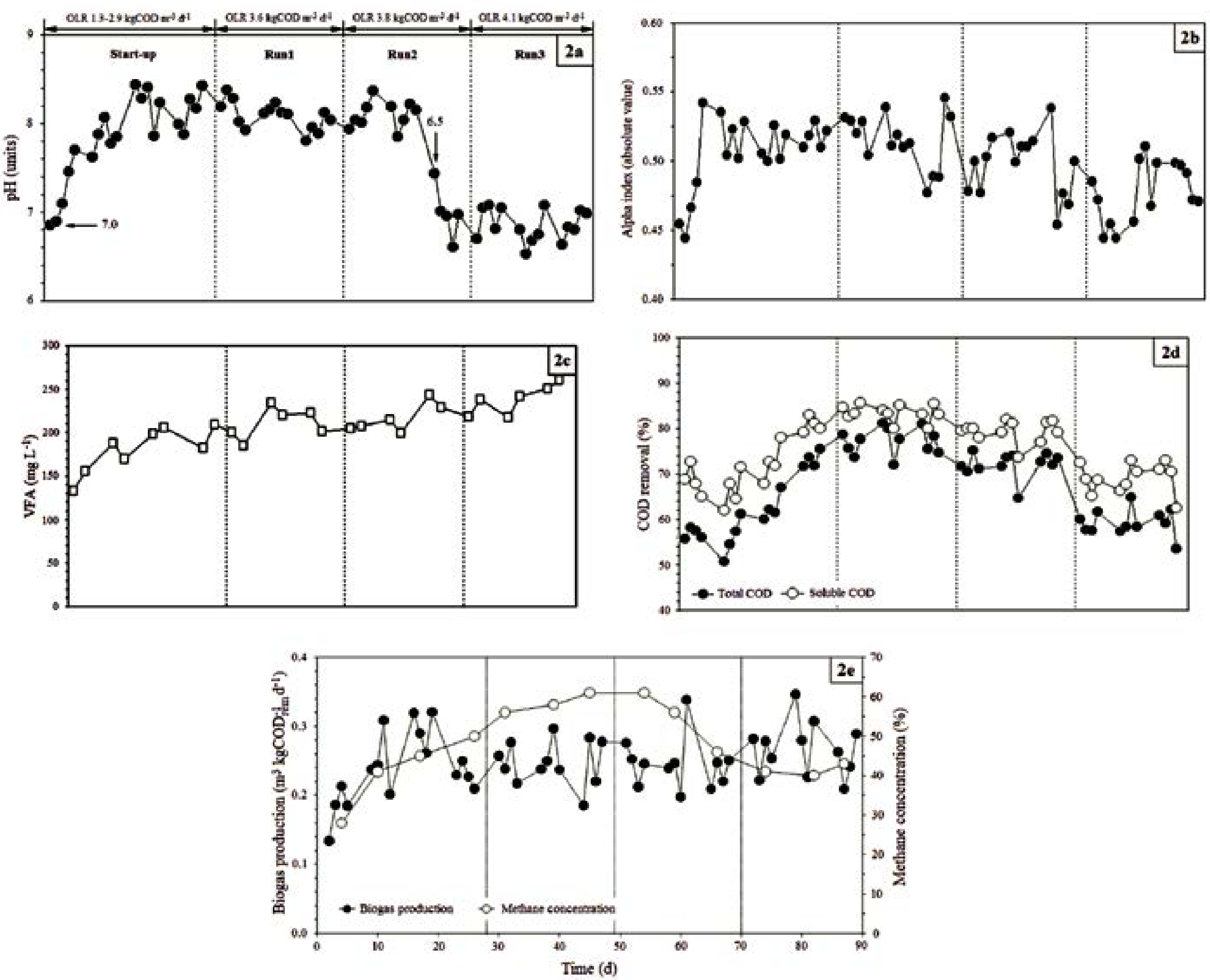

FIGURE 2. Performance of the UASB system; a) pH; b) Alpha index; c) VFA concentration; d) total and soluble COD removal efficiency; e) Biogas production and methane concentration.

Therefore, the VFA increase in the effluent reveals an increase in the load applied to the system. As expected, Run 1 resulted in the lowest VFA concentration in the effluent, with an average value of 220±18 mg L^{-1}, although not significant differences were observed between Run 1 and Run 2. However, Figure 2c shows that in Run 2 the concentration of these acids increased. These results indicated that the HRT did not affect the relative composition of the organic acids in the effluent, but their concentration increased when the OLR increased. Acetic acid reached the higher proportion (60%) followed by propionic acid (28%) and butyric acid (12%), with concentrations of 131±10 mg L^{-1}, 63±7 mg L^{-1} and

26±2 mg L^{-1}, respectively. These percentages reveal an adequate proportion of these acids in the effluent that avoids the inhibition of the anaerobic digestion by VFA (Speece, 1996).

Total and soluble COD removal efficiency

Total COD removal efficiency with the increase in the applied OLR can be seen in Figure 2d. Significant differences were observed between the efficiencies in all the treatments compared, with average values of 77,2%, 72,1% and 59,2% for Run 1, Run 2 and Run 3, respectively (*p*-value>0,05). These results confirm that when the load applied to the system increases, the methanogenic bacteria can not completely degrade the VFA produced; therefore the efficiency and stability of the reactor are affected negatively (Wang *et al.,* 2009). For the first OLR evaluated (Run 1), the soluble COD removal efficiency exhibited a high value (83,4%), indicating a successful treatment of the wastewater in study.

Biogas production and methane concentration generated in the UASB system are shown in Figure 2e. The largest biogas productions were obtained in Run 1. Although, significant differences (*p*-value<0,05) were observed between the biogas obtained in Run1 and Run 2, their respective average values were similar. The total biogas production fluctuated in the range of 0,186-0,346 m^3 $kgCOD^{-1}_{rem}$ d^{-1}, revealing that the effect of the HRT in the conversion of the organic residual to biogas was not significant. According to Lin *et al.* (1986), the biogas production is independent of the HRT and the substrate concentration.

Biogas production and methane concentration

Methane concentration decreased in Run 3. The highest methane concentration values were achieved both in Run 1 and Run 2 (61%) This circumstance indicated an indirect correlation between the VFA concentration and methane concentration because methane production decreased when the VFA concentration increased. These results coincide with those reported by Dogan *et al.* (2005), who studied the effect of the variety and concentration of the VFA in a UASB reactor, and concluded that these factors have a significant effect on the methanogenic activity, besides their synergy with other products. Nevertheless, the main factor affecting the single-stage system was the pH, because when it was adjusted to 6,5 in the wastewater to treat (day 64) a decrease in the methane concentration values were observed. Other authors have also reported an increase in the CO_2 concentration in the biogas with a pH drop (Chen *et al.,* 2008, Leitão *et al.*, 2006, Singh and Prerna, 2009, Bengtsson *et al.*, 2008).

Final discussion

Table 3 shows a summary of the results of multiple range analysis test (Duncan). In UASB system, the VFA concentration in the treated effluent increased slightly, and not significantly, with OLR increase. In Run1, total and soluble COD removal efficiencies were higher (above 75%). The effect of the OLR in the UASB system was no significant in the biogas production; therefore increasing the OLR did not imply any increase in the amount of biogas produced. However, significant differences were observed in the methane concentration.

TABLE 3. Duncan´s multiple range test

OLR (kgCOD m^{-3} d^{-1})	Variables response				
	VFA concentration (mg L^{-1})	Total COD removal (%)	Soluble COD removal (%)	Biogas production (m^3 $kgCOD^{-1}_{rem}$ d^{-1})	Methane concentration (%)
Run1	210,5±18 B	77,2±2,93 A	83,4±1,87 A	0,25±0,03 A	58,3±0,03 A
Run2	216,3±17 B	72,1±2,73 B	79,4±2,35 B	0,24±0,03 A	45,3±0,07 B
Run3	237,8±17 A	59,2±2,93 C	69,1±3,31 C	0,27±0,04 A	41,3±0,02 C

For each variable, means in each column followed by the same upper case letter are not significantly different between OLR and HRT (*p*-value<0,05)

A summary of publications related to the anaerobic treatment of coffee processing wastewaters is presented in Table 4. In our study, a UASB reactor, operated at an OLR of 3,6 kgCOD m^{-3} d^{-1}, achieved a total and soluble COD removal efficiency of 77,2±2,9% and 83,5±1,87%, respectively, and a methane concentration of 58±2,5%. These results are comparable with those reported by other authors. Fernández and Foster (1993), operating two anaerobic filters at 37°C and 55°C, with an OLR of 4,0 kgCOD m^{-3} d^{-1}, observed a COD removal efficiency of 63%, treating a synthetic wastewater made up of coffee bean extract. Silva and Campos (2005) studied the feasibility of a laboratory scale UASB reactor that was used to treat coffee wet wastewater. The wastewater pollutant load was 3250 mg L^{-1}, the system operating conditions were adjusted to an HRT of 69 hours and an OLR of 0,59 $kgCODm^{-3}$ d^{-1}, and the COD removal efficiency achieved was 78%, Recently, Fia *et al.* (2012) evaluated three different support materials in an AFBR anaerobic reactor and the largest COD removal efficiency, 80%, was obtained at an OLR of 4,4 kgCOD m^{-3} d^{-1}.

TABLE 4. Summary of some publications related to the anaerobic digestion of the coffee wastewaters processing

Reactor	OLR (kgCOD m^{-3} d^{-1})	HRT (h)	Temperat. (°C)	COD removal efficiency (%)	Methane concentrate. (%)	References
UAF	4	24	37-55	63	70	Fernández and Foster (1993)
UAF	3,33	-	37	65	55	McDougall *et al*. (1993)
CSTR	1,3-1,6	20-25*	35-55	60	65-70	Dinsdale *et al*. (1996)
Hybrid UASB-UAF	1,89	22	-	77,2	-	Bello-Mendoza and Castillo-Rivera (1998)
UASB	0,59	69	-	78	-	Silva and Campos (2005)
UASB	-	-	22-27	70-82	48-68	Calil *et al.* (2010)
Hybrid UASB-UAF	9,55	18	-	61	58	Selvamurugan *et al.* (2010a)
Hybrid UASB-UAF	7,01	24	-	70	60	Selvamurugan *et al.* (2010b)
AFBR	4,41	25,4	6,4-32,9	80	-	Fia *et al*. (2012)
UASB (This study)	3,6	21,5	35	77,2	58	

CONCLUSIONS

- Coffee wet wastewaters were successfully treated in a single-stage UASB reactor. Both total and soluble COD removal efficiencies observed were higher than 75% and 80%, respectively, at an OLR of 3,6 kgCOD m^{-3} d^{-1}, whereas the methane concentration was in a range of 56-61%, with aptitudes of being used like power source by the conversion to electrical energy. On the basis of this study we reached that an anaerobic UASB reactor is a suitable system of treat wastewaters of coffee wet processing.

REFERENCES

APHA: *Standard methods for examination of water and wastewater,* Nineteenth ed. American Public Health Association, Washington D.C., USA., 1995.

BELLO-MENDOZA, R. y CASTILLO-RIVERA, M.: "Start-up of an anaerobic hybrid (UASB/Filter) reactor treating wastewater from a coffee processing plant" *Anaerobe,* 4**:** 219-225, 1998.

BENGTSSON, S., HALLQUIST, J., WERKER, A. y WELANDER, T.: "Acidogenic fermentation of industrial wastewater: Effect of chemostat retention time and pH on volatile acids production" *J. Environ. Eng.,* 40**:** 492-499, 2008.

BOUALLAGUI, H., TORRIJOS, M., GODON, J., MOLCTTA, R., CHEIKH, R., TOUHAMI, Y., DELGENES, J. y HAMDI, M.: "Two-phase anaerobic digestion of fruit and vegetable wastes: Bioreactors performance" *J. Biochem. Eng.,* 21**:** 193-197, 2004.

CALIL, M., MONTENEGRO, C. y FERREIRA, J.: "Estudo da variação da concentração de metano no biogás produzido a partir das águas residuárias do café" *Ciënc. Agrotec. Lavras,* 34**:** 475-484, 2010.

CHEN, Y., CHENG, J. y CREAMER, K.: "Inhibition of anaerobic digestion process: A review" *Bioresour. Technol,* 99**:** 4044-4064, 2008.

DEVI, R., SINGH, V. y KUMAR, A.: "COD and BOD reduction from coffee processing wastewater using Acavado pell carbon" *Bioresour. Technol.,* 99**:** 1853-1860, 2008.

DINSDALE, R., HAWKES, F. y HAWKES, D.: "The mesophilic and termophilic anaerobic digestion of coffee waste containing coffee grounds" *Wat. Res,* 30**:** 371-377, 1996.

DINSDALE, R., HAWKES, F. y HAWKES, D.: "Comparision of mesophilic and thermophilic UASB reactors treating instant coffee production wastewater" *Wat. Res.,* 31**:** 163-169, 1997a.

DINSDALE, R., HAWKES, F. y HAWKES, D.: "Mesophilic and thermophilic anaerobic digestion with thermophilic pre-acidification of instant coffee production wastewater" *Wat. Res.,* 31**:** 1931-1938, 1997b.

DOGAN, T., INCE, O., OZ, N. y INCE, B.: "Inhibition of volatile fatty acid production in granular sludge from a UASB reactor" *Environ. Technol.,* 40**:** 633-644, 2005.

FERNÁNDEZ, N. y FOSTER, C.: "A study of the operation of mesophilic and thermophilic anaerobic filters treating a syntetic coffee waste" *Bioresour. Technol.,* 45**:** 223-227, 1993.

FIA, F., MATOS, A., BORGES, A., FIA, R. y CECON, P.: "Treatment of wastewater from coffee bean processing in anaerobic fixed bed reactors with different support materials: performance and kinetics modeling" *J. Environ. Managem.,* 108**:** 14-21, 2012.

GUARDIA-PUEBLA, Y., NOYOLA, A. y MORGAN-SAGASTUME, J.: Two-stage anaerobic digestion treating wastewater from wet processing of coffee. In*:* 12th World Congress on Anaerobic Digestion, International Water Association (IWA), In: Specialist Conferences, october 31st - november 4th, Guadalajara, Jalisco, México, 2010.

HAJIPAKKOS, C.: "The application of a full-scale UASB plant for the treatment of coffee waste" *Wat. Sci. Tech.,* 25**:** 17-22, 1992.

HOUBRON, E., LARRINAGA, A. y RUSTRIAN, E.: "Liquefaction and methanization of solid and liquid coffee wastes by two phase anaerobic digestion process" *Wat. Sci. Tech.,* 48**:** 255-262, 2003.

JENKINS, S., MORGAN, J. y SAWYER, C.: "Measuring anaerobic sludge digestion and growth by a simple alkalimetric tritation" *Journal of the Water Pollution Control Federation,* 55**:** 448-453, 1983.

LEITÃO, R., HAANDEL, A. V., ZEEMAN, G. y LETTINGA, G.: "The effects of operational and environmental variations on anaerobic wastewater treatment system: A review" *Bioresour. Technol.,* 97**:** 1105-1118, 2006.

LIER, J. V.: "High rate anaerobic wastewater treatment: diversifying from end of the pipe treatment to resource oriented conversion techniques" *Water Sci. Technol.,* 57**:** 1137-1147, 2008.

LIN, C., SATO, K., NOIKE, T. y MATSUMOTO, J.: "Methanogenic digestion using mixed substrate of acetic, propionic and butyric acids" *Wat. Res,* 20**:** 385-394, 1986.

MCDOUGALL, F., ANDERSON, G. y EVISON, L.: Two-phase anaerobic digestion of coffee wastewater, In*:* 48th Purdue Industrial Waste Conference Proceedings, 677-683, 1993.

NAGAO, N., TAJIMA, N., KAWAI, M., NIWA, C., KUROSAWA, N., MATSUYAMA, T., YUSOFF, F. y TODA, T.: "Maximun organic loading rate for the single-stage wet anaerobic digestion of foof waste" *Bioresour. Technol,* 118**:** 210-218, 2012.

NARASIMBA, K., D´SA, A. y KAPUR, G.: "An effluent treatment-cum-electricity generation at coffee estates: is it financially feasible?" *International Energy Iniciative,* 2004.

NEVES, L., OLIVEIRA, R. y ALVES, M.: "Anaerobic co-digestion of coffee waste and sewage sludge" *Waste Management.,* 26**:** 176-181, 2006.

OROZCO, C., BARRIENTOS, H., LÓPEZLENA, A., CRUZ, J., SELVAS, C., OSORIO, E., OSORIO, E., CHÁVEZ, R., MIRANDA, J., ARELLANO, J. y GIESSEMAN, B.: "Evaluación de una planta piloto de tratamiento de aguas residuales del procesamiento del café: características químicas" *Hig. Sanid. Ambient.,* 5**:** 123-131, 2005.

PÉREZ, A. y TORRES, P.: "Índices de alcalinidad para el control del tratamiento anaerobio de las aguas residuales fácilmente acidificables" *Ingeniería Sanitaria,* 10**:** 41-52, 2008.

ROMLI, M., GREENFIELD, P. y LEE, P.: "Effect of recycle on a two-phase high-rate anaerobic wastewater treatment system" *Wat. Res.,* 28**:** 475-482, 1994.

SELVAMURUGAN, M., DORAISAMY, P. y MAHESWARI, M.: "An integrated treatment system for coffee processing wastewater using anaerobic and aerobic process" *Ecological Engineering,* 36**:** 1686-1960, 2010a.

SELVAMURUGAN, M., DORAISAMY, P., MAHESWARI, M. y NANDAKUMAR, N. B.: "High rate anaerobic treatment of coffee processing wastewater using upflow anaerobic hybrid reactor" *J. Environ. Health Sci. Eng.,* 7**:** 129-136, 2010b.

SILVA, B. y CAMPOS, C.: Tratamento anaeróbio de efluentes líquidos gerados no beneficiamento úmido do café. In*:* Congresso Brasileiro de Engenharia Agrícola, 34, Canoas, Anais, Jaboticabal: Associaçâo Brasileira de Engenharia Agrícola, 2005.

SINGH, S. y PRERNA, P.: "Review of recent advances in anaerobic packed-bed biogas reactor" *Renewable and Sustainable Energy Reviews,* 13**:** 1569-1575, 2009.

SPEECE, R. *Anaerobic biotechnology for industrial wastewaters,* Ed. Archea Press, Nashvile, Tennessee, USA, 1996.

WANG, Y., ZHANG, Y., WANG, J. y MENG, L.: "Effects of volatile fatty acid concentrations on methane yield and methanogenic bacteria" *Biomass & Bioenergy,* 33**:** 848-853, 2009.

WARD, A., HOBBS, P., HOLLIMAN, P. y JONES, D.: "Optimization of the anaerobic digestion of agricultural resources" *Bioresour. Technol.,* 99**:** 7928-7940, 2008.

Recibido: 13 de noviembre de 2012.
Aprobado: 28 de enero de 2014.

Yans Guardia Puebla, Prof. Asistente, Universidad de Granma (UDG), Departamento de Ciencias Técnicas, Carretera Manzanillo, km 17 ½, Peralejo, Bayamo, CP 85100, Cuba. Correo electrónico: yguardiap@udg.co.cu

Nota: La mención de marcas comerciales de equipos, instrumentos o materiales específicos obedece a propósitos de identificación, no existiendo ningún compromiso promocional con relación a los mismos, ni por los autores ni por el editor.