Vol. 19, Sup. 1 (2020) 9-16
Revista Mexicana de Ingeniería Química

# Industrial wastewater treatment by anaerobic digestion using a solar heater as renewable energy for temperature-control

# Tratamiento de un agua residual industrial por digestión anaerobia empleando un calentador solar como energía renovable para el control de temperatura

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Received: April 16, 2020; Accepted: June 29, 2020

## Abstract

The clean energies have been the only renewable energies that are capable to replace the use of fossil fuels. The use of clean energies in Wastewater Treatments Plants would decrease the operating costs. In the present work, a solar heater of 8 tubes was used for controlling the temperature of an UASB reactor in order to treat a mixture of industrial wastewater under anaerobic digestion. The reactor was operated at three temperatures (16, 20, and 30 ºC), at organic loading rate of 11 g COD/L-d, HRT of 6 h, and during a period of 100 days. In addition, the effect of a co-substrate on COD consumption was evaluated, in batch cultures. In the steady-state, COD removal efficiencies were 8.6, 20, and 40 %, for 16, 20, and 30 ºC, respectively. Increasing the temperature enhanced the methane production, achieving in average 257 ± 8.6 ml $CH_4$/ g COD removed. In batch cultures, 200 and 400 mg glucose/L used as co-substrate significantly improved the removal and COD consumption rates. Finally, a solar heater might be feasible and economical technology for temperature-control of an UASB reactor in order to improve the organic matter removal.

*Keywords*: solar-heater, anaerobic-digestion, temperature-control, wastewater.

## Resumen

Las energías limpias son las únicas energías renovables capaces de reemplazar el uso de los combustibles fósiles. El uso de las energías limpias en las Plantas de Tratamiento de Aguas Residuales disminuye los costos de operación. En el presente trabajo, un calentador solar se empleó para controlar la temperatura de un reactor UASB con el propósito de depurar un agua residual industrial compleja por digestión anaerobia. El reactor se operó con tres temperaturas (16, 20 y 30 ºC), 11 g DQO/L-d y un TRH de 6 h. Además, se evaluó el efecto de un co-sustrato en la degradación de la DQO, en cultivos lote. En el estado estacionario, las eficiencias de remoción de la DQO fueron de 8.6, 20 y 40%, para las temperaturas de 16, 20 y 30 ºC, respectivamente. El incremento de la temperatura mejoró la producción de metano, alcanzando 257 ± 8.6 ml $CH_4$/g DQO removida. La adición de 200 y 400 mg glucosa/L en cultivos lote mejoraron las eficiencias de remoción y la tasa de consumo de la DQO. Finalmente, un calentador solar podría ser una tecnología factible para controlar la temperatura de un reactor UASB y mejorar la eficiencia de degradación de la materia orgánica.

*Palabras clave*: calentador solar, digestión anaerobia, control, agua residual.

## 1 Introduction

The clean energies are the only renewable energies that are capable to replace the use of fossil fuels. The population growth and technological development have generated a persistent increase in energy demand. Therefore, the finite nature of the resources has forced to develop the potential of the use of non-fossil energy sources. In order to operate Wastewater Treatment Plants (WWTPs) is required electrical energy, for

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*https://doi.org/10.24275/rmiq/IA1853*
*ISSN*:1665-2738, *issn-e*: 2395-8472

example, in Mexico the 90% of electrical energy is produced from fossil fuels that increases the releasing of greenhouse gasses. Thus, the use of clean energies such as wind, solar, bioenergy, hydropower among others, would decrease the operating costs of WWTPs and would mitigate greenhouse gas emissions and the serious consequences of climate change from the use of fossil fuels.

Aerobic and anaerobic biological processes have been used for treating industrial wastewaters. However, aerobic processes such as the activated sludge produces more sludge rather than anaerobic process. The sludge treatment increases significantly the costs for building the WWTPs as well as the operating costs. Moreover, aerobic systems require electricity to supply air to the secondary treatment thus contributing to the greenhouse gas emissions. On the other hand, anaerobic digestion is recognized as a clean technology that associates wastewater treatment with clean energy generation (biogas), being a sustainable alternative. Biogas as a generator of electrical energy is considered a renewable energy that would contribute to increasing energy security. Biogas is a clean renewable energy that promises to be a good substitution for traditional fossil fuels (Krause *et al*., 2008; Gómez-Guerrero *et al*., 2019; Romero-Flores *et al*., 2019). The anaerobic digestion is considered as consolidated technology to treat wastewater polluted with high content of organic matter, and it has been applied to several sectors such as agro-food industry, beverage, alcohol distillery, pulp industry, textile, paper industries, among others (van Lier 2008; Donoso-Bravo *et al*., 2009; Terreros-Mecalco *et al*., 2009; Alzate-Ibanez, 2018). The anaerobic digestion is an excellent option due to the following benefits: minimal production of sludge, low operating costs, biogas production (for heat and electrical energy production), sludge production can be used as bio-fertilizer after a post-treatment, and the wastewater treated after chlorination can be reused for green area irrigation or fish farming. In this context, the anaerobic digestion should be promoted to be collocated as the main technology to treat wastewaters for being a closed circuit and sustainable technology, thus diminishing of using fossil fuels.

The anaerobic digestion is a complex process combining extracellular enzymatic activity and biochemical reactions, which can be categorized in four steps: *Hydrolysis*, *Acidogenesis*, *Acetogenesis* and *Methanogenesis*. The *Hydrolysis* is the first step for the degradation of long chain polymeric organic matter such as lipids, polysaccharides, protein, nucleic acids and fats into soluble organic molecules that can be fermented (Botheju and Bakke, 2011; Rivas-García *et al*., 2020). In the *Acidogenic* pathway, the hydrolysis products are biotransformed into volatile fatty acids (acetic, propionic, butyric, valeric, caproic and heptanoic), and $CO_2$, $H_2$ and ethanol (Appels *et al*., 2008). In the *Acetogenic* pathway, the volatile fatty acids as well as the ethanol are degraded to acetate (Botheju and Bakke, 2011). In the last step, methane production occurs via two methanogenic pathways, *Aceticlastic Methanogenesis* (using acetate) and *Hydrogenotrophic Methanogenesis* (using $H_2$) (Krause *et al*., 2008). About 65-70% of methane is generated through the *Aceticlastic Methanogenesis* pathway (Fukuzaki *et al*., 1990). The anaerobic digestion is governed by the kinetics of the slowest step, being the methanogenesis, however, when treating complex organic matter at low temperature, the *Hydrolytic* step is commonly the limiting step (Donoso-Bravo *et al*., 2009). The temperature increases the rate of organic matter removal, going from psychrophiles to thermophiles conditions (Sanchez *et al*., 2001).

The main goal was to treat a mixture of industrial wastewaters from an industrial zone by anaerobic digestion using an instrumented UASB reactor with solar heater as renewable energy for temperature-control.

## 2 Materials and methods

### 2.1 Reactor configuration and start-up

The whole treatment process was performed at the laboratory where temperature was supplied using an 8-tube solar heater (Figure 1). The UASB reactor was constructed of glass material, with an inner diameter of 10 cm. The total volume of the UASB reactor was of 2.4 L with a working volume of 2.0 L. Six hundred milliliters of granular anaerobic sludge was collected from a local Wastewater Treatment Plant for seeding the system. The reactor was inoculated with 35 ± 2.3 g TSS/L (27 ± 1.5 g VSS/L). The UASB reactor was operated at Hydraulic Retention time (HRT) of 6 h, for a period of 100 days. The system was integrated by a jacket, through which hot water was circulated to regulate the temperature inside the reactor. The industrial wastewater was collected from Wastewater Treatment Plant using an Activated Sludge System, which is treating a mixture of more than 150

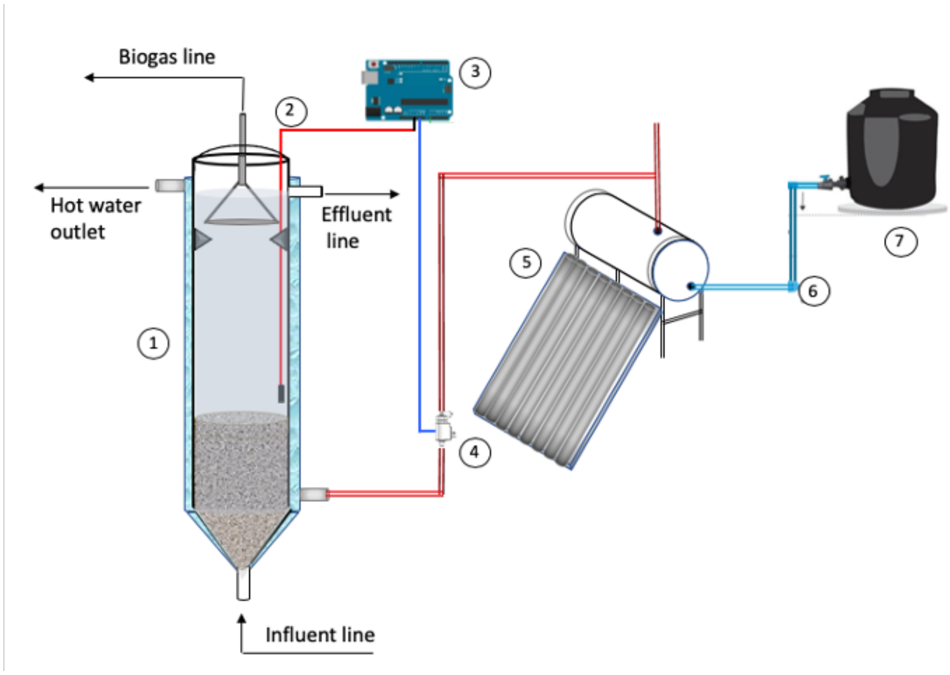

Figure 1. Configuration and instrumentation of the UASB reactor. 1) UASB reactor, 2) temperature sensor, 3) microprocessor Arduino, 4) solenoid valve, 5) solar heater of 8 tubes, 6) check valve, and 7) container of water.

industries such as food industries, pharmaceuticals, textile industries, among others. The liquid sample of industrial wastewater was collected after the primary treatment. The biodegradability index ($BOD_5$/COD) of this kind of wastewater was 0.45, the total nitrogen concentration was 149 ± 15 mg N/L, 2.5 ± 0.2 g of COD/L, and pH of 7.3 ± 0.2. The UASB reactor was evaluated in three stages. In stage I, bioreactor was fed at a loading rate of 11.29 g COD/L-d at 16.42 ± 1.07 ºC. In stage II, the loading rate was of 11.01 g COD/L-d at 22.68 ± 0.08 ºC, whereas in the stage III, the reactor was fed at a loading organic rate of 11.67 g COD/L-d at 30.20 ± 0.67 ºC.

## 2.2 *Instrumentation for temperature-control*

The electronic system was formed by Arduino® microcontroller as an automatic control system, an electronic valve as hot water access (PD02022), a solid-state relay as a digital switching device that switches on or off, a temperature sensor (DS18B20), and a power source (Model Keithley). A closed loop temperature control system was designed and constructed, which compiles the magnitude of temperature from the reaction zone by means of an isolated temperature sensor. The information was decoded and transmitted to a computer that compares the data with the optimum temperature for adjustment. The monitoring system uses an on/off control law, which reduces the error due to temperature difference with an actuator stage (solenoid valves), which regulates the flow of hot water, and the water supply time from solar heater.

## 2.3 *Effect of co-substrate on COD consumption rate*

Serological bottles were used for evaluating the effect of co-substrate (glucose) on methanogenic activity. The batch cultures were incubated by duplicate at 30 ± 2 ºC and 150 rpm. The oxygen was purged from each experiment during 5 min with helium gas. The batch cultures were spiked with 4.0 g VSS/L (i.e. from the last stage) and two initial glucose concentrations were evaluated, 200 and 400 mg/L, plus 1000 mg COD/L contained in the industrial wastewater. Control cultures with only glucose and industrial wastewater were performed. The COD consumption specific rates were computed using the Gompertz model (Origin 8.0, OriginLab, Inc. ®) (González-Blanco *et al*., 2020).

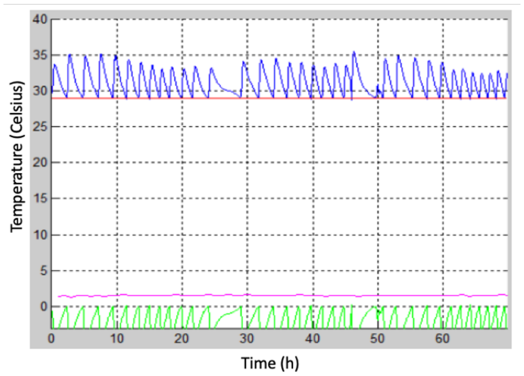

Figure 2. Temperature-control by using the microprocessor. Red line: reference temperature programmed. Blue line: real temperature inside the UASB reactor.

### 2.4 *Monitoring and analytical methods*

Temperature, pH, COD concentrations in the influent and effluent, and biogas production were monitored three times a week. The biogas was collected in an inverted column containing saline solution (200 g NaCl/L, pH 2). The soluble Chemical Oxygen Demand (COD) was quantified by the method of closed reflux. The volatile suspended solids (VSS) were determined according to the standard methods (APHA, 2005), and methane was identified by gas chromatography-TCD (GOW-MAC Instrument 508).

## 3 Results and discussion

### 3.1 *Reactor start-up and performance*

Initially, UASB reactor was instrumented in order to control the temperature inside the reaction zone. In Figure 2 can be seen the temperature control and monitoring at 30 ºC. The red line is the reference temperature programmed, while the blue line is the real temperature inside the UASB reactor. The instrumentation system allowed the good control of temperature inside the reactor, for example the annual temperature of the location (Lerma, Mexico) where the bioreactor was installed and operated was around 12-16 ºC, in spite of this climate conditions, the solar heater managed to reach an average temperature of 30 ºC. At industrial level for heating anaerobic reactors, the water vapor has been used to transfer the heat by serpentine tubes into the reaction zone, but it increases the operating costs. Ren *et al.* (2012) investigated the use of solar panels for anaerobic sewage treatment achieving good results. However, the use of solar heater has more advantages regarding the clean energies such as wind power or solar panels due to the solar heater does not require power converts. Besides the wastewater treated can be used and recycled in the solar heater. In addition, the use of solar heater in places with cold weather might be an excellent option, due to the control of temperature is too expensive. To the best of our knowledge, this is the first time using a solar heater for temperature-control of an UASB reactor.

pH, temperature and ammonia are the most significant governing parameters for anaerobic digestion in order to maintain it at an optimum level (Arshad *et al.*, 2011). Neutral pH is suggested to be the most appropriate range for anaerobic digestion (Bhatti, 1995). However, the anaerobic digestion pathway could take place from 6.5-8.0 (Cioabla *et al.*, 2012). In the present work, in all stages, pH in the influent was neutral, whereas in the effluents were between 7.8-8.1. On the other hand, total ammonium concentration may inhibit the anaerobic digestion. Rajagopal *et al.* (2013) showed that levels of ammonia, up to 200 mg/L, assure adequate supply of nutrients for anaerobic process and increase the buffer capacity counteracting the acidification due to the volatile fat acids production. But ammonia concentration exceeding the critical threshold is detrimental to the anaerobic digestion due to its toxic effect (Polizzi *et al.*, 2018). For example, Chen *et al.* (2016) observed in a food wastewater treatment a strong inhibition of methanogenesis when ammonia overcome 2 g/L. In the present work, total nitrogen did not exceed 200 mg/L, therefore the inhibitory phenomenon linked to ammonia can be negligible.

In Figure 3 is shown the COD profile and removal efficiencies in the UASB reactor operated at HRT of 6 h. In stage I, a steady stage was achieved in 10 days, after this period of time, the stabilized biological process showed COD removal efficiency of 8.6 ± 4 %. Methane production was not observed. The low COD removal efficiency and lack of methane production might be linked to the psychrophilic conditions. Cysneiros *et al.* (2011) showed that methanogenesis was the rate-limiting at 10 °C. Gunnigle *et al.* (2015) observed that sub-unite of methyl-coenzyme M reductase which catalyzes the last step of methanogenesis displayed reduced levels of expression at a temperature of 7 ºC, whereas at 37 ºC the levels of expression of this protein were 18.6-fold-higher.

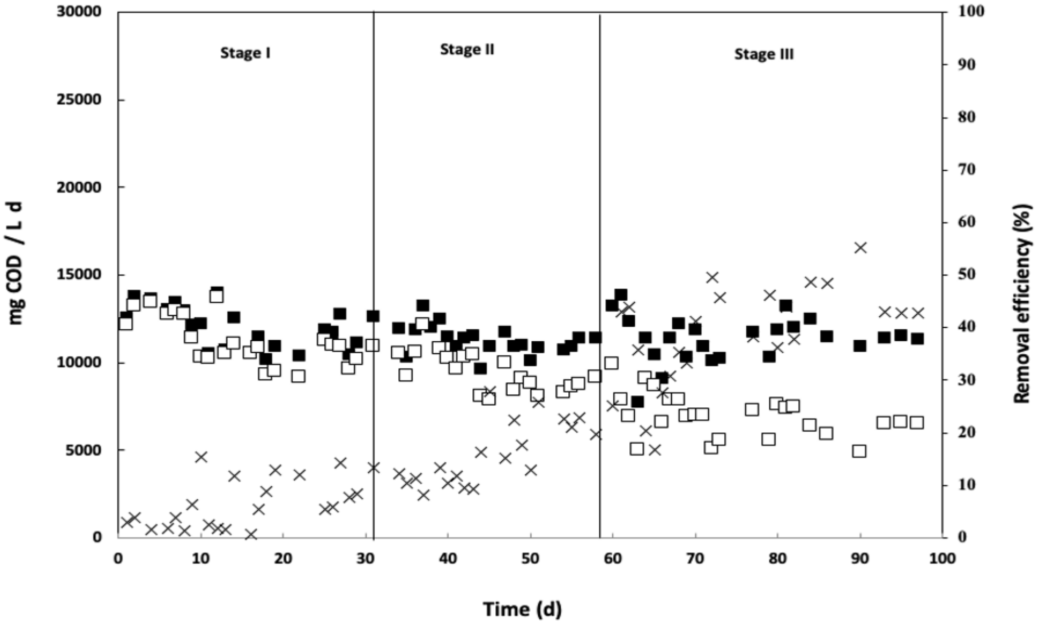

Figure 3. Performance of the UASB reactor operated in continuous, at different temperatures. (□) COD/L-d (effluent), (■) mg COD/L-d (influent), (×) COD removal efficiency.

In stage II, in the steady state, COD removal efficiency increased to 20 ± 4 %, with a methane production of 153 ± 40 ml $CH_4$/ g COD removed. Lin *et al*. (2016) showed that temperature affects anaerobic digestion performance due to the shift of microbial community structure, diversity, and biological activity. For example, Bialek *et al*. (2012) and Cysneiros *et al*. (2011) observed that hydrolysis step had the rate-limiting step at 15 °C. Bialek *et al*. (2013) observed that anaerobic digestion of diluted dairy wastewater was possible at 10 ºC, at organic loading rate up to 2 Kg COD/$m^3$-d achieving COD removal efficiencies above 84%. In the present work, the organic loading rate tested was higher compared to the work of Bialek *et al*., and the chemical composition of the wastewater was very complex, therefore both factors might be involved in low COD degradation.

Finally, at stage III, COD removal efficiency and methane production reached was 40 ± 11 % and 257.73 ± 8.6 ml $CH_4$/ g COD removed, respectively. For example, Lin *et al*. (2016) observed a linear trend for methane production when temperature was increased from 25 to 50 ºC. Donoso-Bravo *et al*. (2009) also observed that COD consumption rate increased linearly when temperature was increased from 15 to 40 ºC. In the present work, the low COD removal attained at 30 ± 2ºC might be due to the complex chemical composition of wastewater, low biodegradability index, and high organic loading rate tested. Arshad *et al*. (2011) evaluated different organic loading rates (from 0.2 to 2.5 g COD/L-d) of textile industrial wastewater by anaerobic digestion, for example, at 1.8 g COD/L-d highest COD removal was observed (around 82%). However, above 1.8 g COD/L-d the removal efficiencies dropped to 65%. Guerrero *et al*. (1999) evaluated extremely high organic loading rates coming

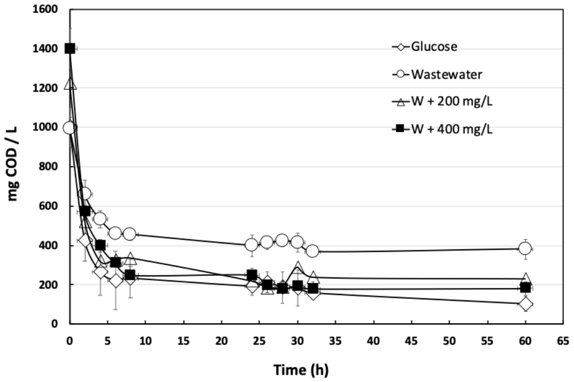

Figure 4. COD consumption profiles in batch cultures. W (industrial wastewater).

Table 1. COD consumption specifics rates and removal efficiencies as result of co-substrate effect, in batch cultures.

| | **q (mg COD/g VSS-h)** | **COD removal efficiency (%)** |
|---|---|---|
| Glucose (gl) | 85 ± 7 | 90 ± 5.3 |
| Industrial water (W) | 38 ± 4.3 | 61 ± 4.7 |
| W + 200 mg gl/L co-substrate | 108 ± 12.6 | 80 ± 7.8 |
| W + 400 mg gl/L co-substrate | 110 ± 5.6 | 87 ± 5.6 |

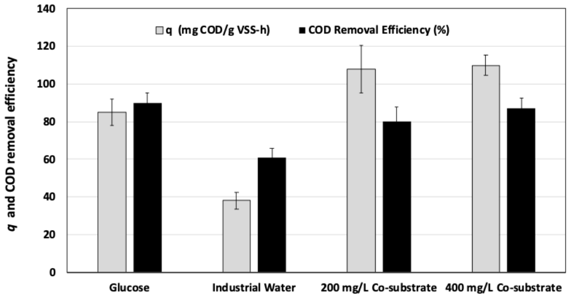

Figure 5. COD consumption specifics rate in batch cultures.

from food industries, up to 400 g COD/L-d, but no significant production of methane was observed. In the present work, in spite of using an industrial wastewater of chemical complexity, increasing the temperature enhanced the COD removal efficiencies as well as the methane production.

### *3.2 Effect of co-substrate on COD consumption rate*

In Figure 4 is shown the effect of co-substrate on COD consumption profiles. The batch culture only spiked with glucose, COD removal efficiency was of 90 ± 5.6 %, with a COD consumption rate of 85 ± 7 mg COD/g VSS-h (Table 1). In the batch culture spiked only with industrial wastewater (as control test), COD removal efficiency was 61 ± 4.7 %, and COD was consumed at a specific rate of 38 ± 4.3 mg COD/g VSS-h. These kinetic results indicated that the complex industrial wastewater influenced the kinetic behavior, perhaps due to the presence of toxic compounds. Now, when 200 mg/L of glucose was used as co-substrate the kinetic behavior improved since COD removal efficiency increased from 61 to 80 ± 7.8 %. The COD consumption rate was 2.8-fold faster regarding the control test (Figure 5). In the second concentration of co-substrate evaluated (400 mg glucose/L), the kinetic behavior did not change significantly. Khan *et al.* (2017) observed the positive effect of glucose as co-substrate for increasing the pentachlorophenol decomposition under anaerobic digestion. The authors observed that sludge in touch with glucose appeared to be quite porous with uniform channels that confirm better mass transfer thus resulting in higher degradation rates. Okada *et al.* (2013) showed that addition of complex co-substrate improved an anionic surfactant removal under anaerobic digestion, as well as an augmentation of anaerobic bacteria since methanogenic was observed. Işik and Sponza (2005) observed that decolorization of congo red azo dye was improved using glucose (i.e. 100-300 mg/L) as co-substrate. These results indicated that the presence of glucose improves the organic matter degradation, and it might be a strategy to enhance the treatment of complex industrial wastewater.

## Conclusions

A solar heater instrumented with an electronic system formed by Arduino® allowed the temperature-control in a UASB reactor for treating a mixture of industrial wastewater of chemical complexity under anaerobic digestion. In the continuous UASB reactor fed with complex industrial wastewater, increasing the temperature from 16 to 30 ºC improved both COD removal efficiency and methane production. In batch cultures, 200 mg glucose/L used as co-substrate enhanced the kinetic behavior of anaerobic digestion, since COD removal efficiency increased from 61 to 80 %, whereas the COD consumption rate was 2.8-fold faster regarding the control without co-substrate.

### *Acknowledgements*

The second author acknowledges the support of the National Council for Science and Technology (CONACyT-Mexico) through a scholarship to attend the doctorate within the Postgraduate of Sciences of the Autonomous Metropolitan University. Part of the project was supported by PRODEP-SEP-UAM-L-CA-3.

## References

Alzate-Ibanez, A. M. (2018). States and variables estimation in an upflow anaerobic sludge blanket reactor for the leachate wastewater treatment using nonlinear observers. *Revista Mexicana de Ingeniería Química 17*, 723-738.

APHA AWWAW (2005). *Standard Methods for Examination of Water and Wastewater*, 21th. APHA, AWWA, WPCR, 1, New York.

Appels, L., Baeyens, J., Degrève, J., and Dewil, R. (2008). Principles and potential of the anaerobic digestion of waste-activated sludge. *Progress in Energy and Combustion Science 34*, 755-781.

Arshad, A., Hashim, N.H., Kashif, A.K., and Bashir, A. (2011). Assessment of the treatment of textile mill effluent using UASB reactor. *ASEAN Journal on Science and Technology for Development 28*, 139-150.

Bhatti, Z.I. (1995). Problems encountered during the start-up of UASB reactor. *Japanese Journal of Water Treatment and Biology 31*, 59-62.

Bialek, K., Cysneiros, D., and O'Flaherty, V. (2013). Low-temperature (10 ºC) anaerobic digestion of dilute dairy wastewater in an EGSB bioreactor: Microbial community structure, population dynamics, and kinetics of methanogenic populations. *Archaea*, 2013.

Bialek, K., Kumar, A., Mahony, T., Lens, P.N., and O'Flaherty, V. (2012). Microbial community structure and dynamics in anaerobic fluidized-bed and granular sludge-bed reactors: influence of operational temperature and reactor configuration. *Microbial Biotechnology 5*, 738-752.

Botheju, D., and Bakke, R. (2011). Oxygen effects in anaerobic digestion-a review. *Open Waste Management Journal 4*, 1-19.

Chen, H., Wang, W., Xue, L., Chen, C., Liu, G., and Zhang, R. (2016). Effects of ammonia on anaerobic digestion of food waste: process performance and microbial community. *Energy & Fuels 30*, 5749-5757.

Cioabla, A.E., Ionel, I., Dumitrel, G.A., and Popescu, F. (2012). Comparative study on factors affecting anaerobic digestion of agricultural vegetal residues. *Biotechnology for Biofuels 5*, 1-9.

Cysneiros, D., Thuillier, A., Villemont, R., Littlestone, A., Mahony, T., and O'Flaherty, V. (2011). Temperature effects on the trophic stages of perennial rye grass anaerobic digestion. *Water Science and Technology 64*, 70-76.

Donoso-Bravo, A., Retamal, C., Carballa, M., Ruiz-Filippi, G., and Chamy, R. (2009). Influence of temperature on the hydrolysis, acidogenesis and methanogenesis in mesophilic anaerobic digestion: parameter identification and modeling application. *Water Science and Technology 60*, 9-17.

Fukuzaki, S., Nishio, N., and Nagai, S. (1990). Kinetics of the methanogenic fermentation of acetate. *Applied Environmental and Microbiology 56*, 3158-3163.

Gómez-Guerrero, A.V., Valdez-Vazquez, I., Caballero-Caballero, M., Chiñas-Castillo, F., Alavéz-Ramírez, R., and Montes-Bernabé, J.L. (2019). Co-digestion of agave *angustifolia* haw bagasse and vinasses for biogas production from mezcal industry. *Revista Mexicana de Ingeniería Química 18*, 1073-1083.

González-Blanco, G., Pérez-Pérez, V., Orozco-Villafuerte, J., Aguirre-Garrido, J.F., Beristain-Cardoso, R., and Buendía-González, L. (2020). Kinetics and microbial structure of nitrogen cycle bacteria contained in the rhizosphere of natural wetland polluted with chromium. *Revista Mexicana de Ingeniería Química 19*, 543-553.

Guerrero, L., Omil, F., Mendez, R., and Lema, J.M. (1999). Anaerobic hydrolysis and acidogenesis of wastewaters from food industries with high content of organic solids and protein. *Water Research 33*, 3281-3290.

Gunnigle, E., Siggins, A., Botting, C. H., Fuszard, M., O'Flaherty, V., and Abram, F. (2015). Low-temperature anaerobic digestion is associated with differential methanogenic protein expression. *FEMS Microbiology Letters 362*, 1-7.

Işik, M., and Sponza, D. T. (2005). Effects of alkalinity and co-substrate on the performance of an upflow anaerobic sludge blanket (UASB) reactor through decolorization of Congo Red azo dye. *Bioresource Technology 96*, 633-643.

Khan, M.D., Khan, N., Nizami, A.S., Rehan, M., Sabir, S., and Khan, M.Z. (2017). Effect of co-substrates on biogas production and anaerobic decomposition of pentachlorophenol. *Bioresource Technology 238*, 492-501.

Krause, L., Diaz, N.N., Edwards, R.A., Gartemann, K.H., Krömeke, H., Neuweger, H., *et al*. (2008). Taxonomic composition and gene content of a methane-producing microbial community isolated from a biogas reactor. *Journal of Biotechnology 136*, 91-101.

Lin, Q., He, G., Rui, J., Fang, X., Tao, Y., Li, J., and Li, X. (2016). Microorganism-regulated mechanisms of temperature effects on the performance of anaerobic digestion. *Microbial Cell Factories 15*, 96.

Okada, D.Y., Esteves, A.S., Delforno, T.P., Hirasawa, J.S., Duarte, I.C.S., and Varesche, M. B.A. (2013). Influence of co-substrates in the anaerobic degradation of an anionic surfactant. *Brazilian Journal of Chemical Engineering 30*, 499-506.

Polizzi, C., Alatriste-Mondragón, F., and Munz, G. (2018). The role of organic load and ammonia inhibition in anaerobic digestion of tannery fleshing. *Water Resources and Industry 19*, 25-34.

Rajagopal, R., Massé, D. I., and Singh, G. (2013). A critical review on inhibition of anaerobic digestion process by excess ammonia. *Bioresource Technology 143*, 632-641.

Ren, Z., Chen, Z., Hou, L. A., Wang, W., Xiong, K., Xiao, X., and Zhang, W. (2012). Design investigation of a solar energy heating system for anaerobic sewage treatment. *Energy Procedia 14*, 255-259.

Rivas-García, P., Botello-Álvarez, J.E., Miramontes-Martínez, L.R., Cano-Gómez, J.J., and Rico-Martínez, R. (2020). New model of hydrolysis in the anaerobic co-digestion of bovine manure with vegetable waste: modification of anaerobic digestion model. *Revista Mexicana de Ingeniería Química 19*, 109-122.

Romero-Flores, M., Sillas-Moreno, M.V., Trejo, E., and Montesinos-Castellanos, A. (2019). Modelling of continuous production of biogas in a tubular reactor. *Revista Mexicana de Ingeniería Química 18*, 803-812.

Sanchez, E., Borja, R., Weiland, P., Travieso, L., and Martin, A. (2001). Effect of substrate concentration and temperature on the anaerobic digestion of piggery waste in a tropical climate. *Process Biochemistry 37*, 483-489.

Terreros-Mecalco, J., Olmos-Dichara, A., Noyola-Robles, A., Ramírez-Vives, F., and Monroy-Hermosillo, O. (2009). Digestión anaerobia de lodo primario y secundario en dos reactores UASB en serie. *Revista Mexicana de Ingeniería Química 8*, 153-16.

Van Lier, J. B. (2008). High-rate anaerobic wastewater treatment: diversifying from end-of-the-pipe treatment to resource-oriented conversion techniques. *Water Science and Technology 57*, 1137-1148.