Diseño de un reactor UASB de escala laboratorio y bajo costo para investigación y enseñanza en laboratorios de bajos ingresos

Design of a low budget lab-scale UASB reactor for research and teaching in low income laboratories

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Resumen

Los reactores anaerobios de manto de lodo de flujo ascendente (UASB) son el sistema más ampliamente implementado para el tratamiento anaerobio de aguas residuales de alto contenido de material orgánico. Aun cuando estos son sistemas altamente eficientes y la producción de metano a partir de agua residual los hace energéticamente atractivos, su implementación en países en desarrollo todavía está retrasada no solo debido a dificultades financieras, sino debido a que su operación es relativamente complicada. Por esta razón, es crucial mantener reactores UASB de escala laboratorio instalados, de manera que se puedan entrenar técnicos y profesionales en este campo. Desafortunadamente, los costos de instalación pueden ser prohibitivos para algunos laboratorios de bajos ingresos. Dado que la literatura científica usualmente hace énfasis en los resultados obtenidos usando reactores UASB, pero rara vez se enfoca en sus detalles de construcción, aquí se presenta una descripción detallada de la construcción de un reactor UASB de bajo costo para investigación y enseñanza en los laboratorios de ingeniería ambiental de la Universidad Antonio Nariño.

Palabras clave: UASB, bajo costo, digestión anaerobia, residuos sólidos porcícolas.

Abstract

Upflow anaerobic sludge blanket reactors (UASB) are the most widely implemented setup for anaerobic treatment of wastewaters with a high organic load. Even though these are very efficient systems and methane production

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from organic waste makes them energetically attractive, its implementation in developing countries is still hampered, not just because of financial reasons, but because of its relatively difficult operation. For this reason, it is crucial to maintain a number of installed lab-scale UASB reactors for training of technicians and professionals. Unfortunately, the installation costs might be prohibitive for low-income laboratories. As scientific literature usually focuses on results obtained using UASB reactors, but rarely focuses on construction details, here we present a detailed description of the building of a low budget UASB reactor for research and instruction in the Antonio Nariño University environmental engineering labs.

Keywords: UASB, low Budget, anaerobic digestion, swine solid waste.

I. INTRODUCTION

Anaerobic biological digestion is a widely used technology with applications on the treatment of wastewater, industrial effluents, agricultural residues, and livestock waste. Unfortunately, its implementation in developing countries and particularly in Colombia is still far behind [1]; even though some studies suggest that the production of biogas from anaerobic digestion is a feasible solution to several environmental and energy issues in these countries [2]–[4]. In general, the barriers for the implementation of this technology in developing countries are not limited to the lack of funding, but are also related to the low understanding about its setup and operation [5], a reason why the construction of lab scale anaerobic reactors for local studies and teaching is important.

The development of low budget prototypes for laboratory studies permits the training of engineers and technicians beyond the theoretical frameworks, focusing on a more experimental approach. There are many efforts in developing countries seeking the development of this low budget prototypes applied to many fields [6], [7], but the results for UASB reactors are rarely published since the papers are usually focused on the process variables but not on the equipment. A quick search using the keywords "*prototipo UASB bajo costo*" in google scholar (August 2015) returns only 92 matches from which less than 5 are actual low budget UASB reactors prototypes [8]–[11], so this technical experiences are not available for other researchers. Scientists and teachers trying to build a UASB reactor from scratch usually face the same problems many others experienced before: reactor temperature control, biogas collection and measurement, and flow regulation. Hence, the lack of information about construction details impedes a faster development of new low-cost prototypes.

In this paper we explain the details about the construction of a low budget UASB reactor for its use in the environmental engineering laboratories at Antonio Nariño University. This reactor cost less than 200 dollars and is currently used for both teaching and research. Besides construction details, we also provide some data about the application of this prototype on the preliminary study of swine waste degradation using granular sludge from an industrial UASB reactor.

I. MATERIALS AND METHODS

A. UASB reactor

The constructed reactor was a cylindrical column (internal diameter: 7.5 cm, height: 60 cm) made of transparent plexiglass. It had 2 plastic valves (1/4"), for sampling, located at 5 and 55 cm from the bottom. The reactor was fed using a plastic valve (3/4") located at 5 cm from the bottom. A 3 phase separator was located at the top of the column (height: 20 cm). The separator had 2 baffles to enhance gas removal and 3 hose adapters (1/4") on the top for escape and collection of the biogas (figure 1). The liquid outlet was a PVC nipple (3/4") connected to an external siphon (figure 2).

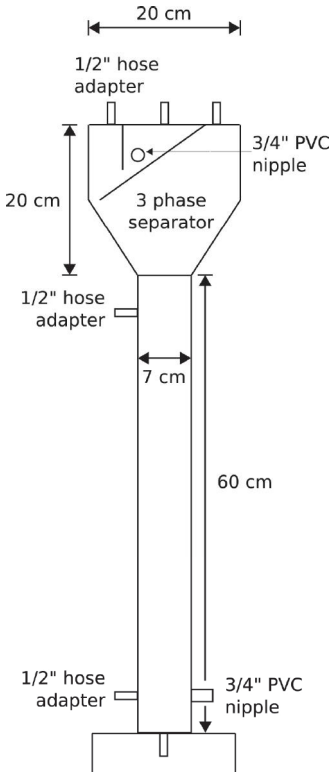

Figura 1. Dimenasions of the UASB reactor column and the 3 phase separator.

B. Heating system

A water-based heating circuit was used for heating the reactor column. A styrofoam box was used as the main water reservoir and 2 aquarium heaters (30 W) were used as heat sources (figure 3). Water was pumped through the circuit by a submersible pump (static head: 80 cm) through a hose (1/2") spiraling around the reactor column and returning to the styrofoam box.

C. Gas collector

The produced biogas was measured by the liquid displacement method. Basically, an inverted graduated cylinder is submerged in water and the gas is bubbled inside. The bubbled gas occupies the volume of the water in the graduated cylinder, displacing the water outwards. As the gas remains trapped in the graduated cylinder, its volume can be easily measured.

Based on this method, the gas collector was built as a plexiglass box with 3 consecutive internal chambers (figure 4). The box was fully filled with water. The first chamber (gas accumulation chamber) was submerged under the water with a 1/4" valve on the top for releasing of the accumulated gas. A gap in the bottom permitted both the entrance of the biogas hose coming from the reactor and the escape of the water displaced by the gas accumulating inside. The second chamber was always full of water and received the displaced water from the gas accumulation chamber. The third chamber served as a recipient for the water spilling from the second chamber.

To absorb all the carbon dioxide from the biogas, NaOH was added to the water in the gas collector so the measured gas volume corresponded mainly to methane [12], [13]. Phenolphthalein was used as pH indicator and the pink color of the solution permitted a rapid confirmation of the presence of non-neutralized NaOH. Measurement of the whole biogas was done by using water instead of the NaOH solution [14], [15]. Alternatively, to avoid depressurization of the reactor when removing the NaOH solution from the gas collector, it was neutralized with carbonic acid (formed by reaction of the carbon dioxide in the biogas with the water in the gas collector) until the solution was saturated with sodium carbonate (when a precipitate was formed [16]).

D. Pumping system and gravity feed tank

The pumping system consisted of a plastic tank reservoir for the liquid feed and a submersible pump (static head: 80 cm) connected to a 1/2" hose. A 1/2" ball valve was used for primary flow regulation. The outlet of this valve was connected to a 1/8" hose and a splitting tee, which returned most of the fluid to the feed reservoir tank. The rest of the fluid entered a dosification system obtained from a venoclysis kit (chamber and roller clamp), facilitating the adjustment of low flow rates. The liquid exiting the dosification system dripped to the gravity feed tank, which was open to the atmosphere. The gravity feed tank was directly connected to the feeding valve of the reactor.

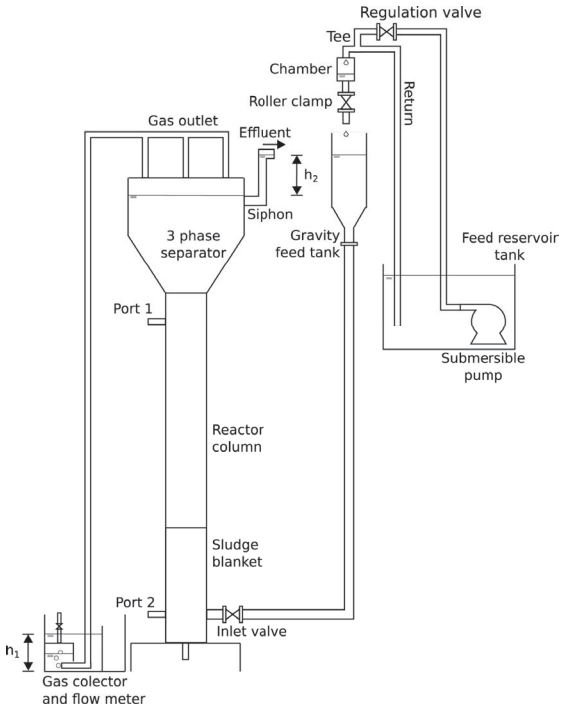

Figura 2. Scheme of the whole UASB reactor setup. Notice the location of the gas collector and the height h_1. The siphon height h_2 defines the height of wastewater in the gravity feeding tank and must be at least equal to h_1 or larger.

E. Methanization assays

The reactor was inoculated with a granular sludge from an industrial UASB reactor treating dairy waste. Swine waste was fed to the reactor diluted in water to reach a COD of 2000 mg/L. The flow was maintained constant at 2 mL/min. Methane production was measured by displacement of a 2.5% NaOH solution [12]. pH was determined using an InoLab potenciometer. Methods from the American Water Works Association were used for determination of alkalinity (2320) and COD (5220) [17]. The reactor was covered from light to minimize algal growth [18].

II. RESULTS

A. Heating system

Although the heating system was not regulated, it maintained the temperature inside the reactor at 35°C ± 2°C (figure 5A), depending on environmental conditions (room temperature). The temperature was adjusted by trial and error modifying the power of the heaters and the length of the hose in contact with the reactor (number of loops in the spiral, figure 3A). The styrofoam box was partially sealed to minimize water escape by evaporation, but still it required a water recharge every 2 weeks.

Since there was no insulation around the reactor, most of the heat was transferred to the surroundings, but the temperature of the water flowing through the spiraling hose dropped only from 65°C to 64°C. Perhaps this is the reason why the temperature inside the reactor did not fluctuate more than 2°C from the average 35°C, when wastewater at 17°C was fed. A simple energy balance shows this situation:

Heat lost by water in the spiraling hose:

0.0049 kg/s * 4.188 kJ/(kg K) * (338.15 K – 337.15 K) = 0.02 kW, where 0.0049 kg/s corresponds to 0.3 L/min of water.

Heat gained by water (wastewater) flowing through the reactor:

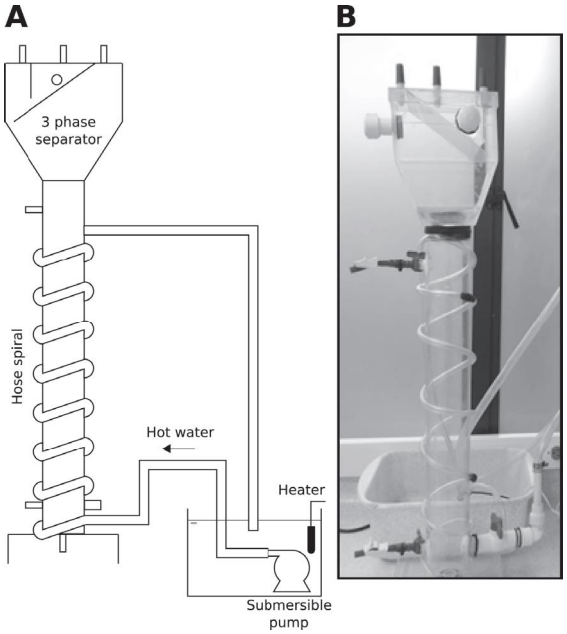

Figura 3. Heating system. Hot water flows through a hose spiraling the reactor column. A) scheme of the heating loop. B) photography of the actual setup.

3.32E-5 kg/s * 4.181 kJ/(kg K) * (308.15 K – 288.15 K) = 0.003 kW, where 3.32E-5 kg/s corresponds to 2 mL/min of wastewater.

In general, 15% of the heat lost by the hot water is gained by the wastewater in the reactor. The rest is lost to the surroundings.

B. GAS COLLECTOR AND HYDRAULICS

The gas collector box was located at the same height with the bottom of the reactor (figure 2). The gas collecting hose discharged into the collection chamber, so the pressure at bottom of the collection chamber equates the pressure at the surface of the liquid inside the 3 phase separator in the reactor. This pressure depended on the height of the water column in the second chamber (h_1) and hence it determined the whole system hydraulics. Since the liquid outlet of the 3 phase separator was connected to a siphon, the biogas was not able to escape through it as long as the siphon height (h_2) was maintained larger than h_1. At the same time, the siphon height also determined the height of the liquid inside the gravity feed tank, which was slightly higher due to the hydraulic losses in the tubing and the sludge blanket. In the end, the designed setup forced each water droplet entering the gravity feed tank to push a similar amount of liquid out of the siphon and all the biogas was directed to the top of the 3 phase separator.

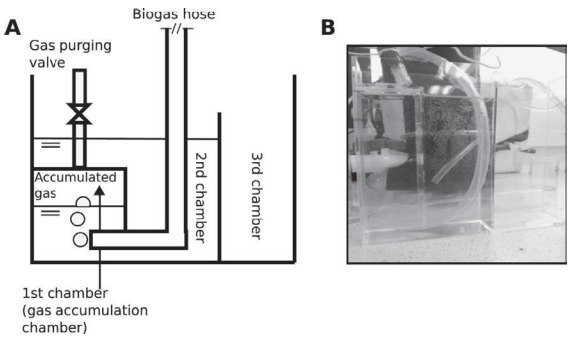

Figura 4. Gas collector. A) scheme of the 3 chambers gas collector. Biogas is accumulated inside the first chamber displacing the NaOH solution to the second chamber. Excess solution spills to the third chamber to maintain a constant water head. B) photography of the actual setup.

C. Pumping system and gravity feed tank

Liquid flow control is usually achieved by the use of a peristaltic pump, which is a relatively expensive piece of equipment. Here we propose the use of a submersible pump ($ 10 dollars) which is almost 30 times cheaper. The main advantage of peristaltic pumps is their capacity to maintain low flow rates, in the order of milliliters per minute, which is not possible with just a regular submersible pump. To solve this problem, a regulator valve was connected to the discharge of the pump. However, while it controlled the flow, the solids suspended in the liquid slowly accumulated in the hose and the valve, obstructing the feeding system almost daily.

The system depicted in figure 2 shows a tee connected to the outlet of the regulation valve. This tee permitted the return of most of the flow to the feed reservoir tank, so the liquid flows at higher speed avoiding obstruction of the main hose. The second outlet of the tee was connected to a venoclysis roller clamp that controls the flow into the gravity feed tank. Although this systems still gets obstructed, it only requires cleaning every 4 to 5 days.

On the other hand, direct connection of this pumping system to the reactor would require to reach a pressure high enough to equilibrate and surpass the pressure of the water column inside the reactor. Since the pumps we are using have only 90 cm of static head, their power would be barely sufficient for the task, and the addition of a check valve to avoid involuntary draining of the reactor makes the pumping even more difficult. Because of this, a gravity feeding tank was chosen as the feeding method, therefore the required pumping power is minimized by elevating the feed reservoir tank and the dripping is easily controlled by a couple of valves.

D. Swine waste methanization

The reactor setup was tested for methanization of swine waste using anaerobic granular sludge. The reactor was operated as a batch system for 5

days loaded with 46 g of water-suspended swine waste (2000 mgCOD/L) and 900 mL of settled granular sludge. Once production of biogas was detected, 3 days after startup, a continuos feed of waste was connected. The reactor was operated during 25 days and 3 parameters were registered: COD, pH, and alkalinity. While measurement of volatile fatty acids has been widely recognized as an important parameter for control [19], a minimum set of control parameters (pH and alkalinity [20], [21]) was considered for this study.

COD was measured in 4 points: the feeding, the two ports in the column, and the effluent. As shown in figure 5B, COD in the feeding was almost constant suggesting that the COD removal happens only in the reactor. COD values measured in the ports and the effluent were mostly similar and showed a constant decrease during the first 15 days to a maximum COD removal of 85%. By the last 10 days, COD values stopped dropping and the COD removal decreased to 63% (figure 5C).

The first control parameter, pH (figure 5E), was determined for samples from the 2 ports and the effluent. It decreased steadily until day 16 when it reached a value of 6.71, at which methanogenesis is no longer favored [22], then 300 mg Na_2CO_3/L were added to the feed [23]. Addition of Na_2CO_3 artificially increased alkalinity and helped to neutralize the excess of acid that causes the drop in pH. By day 18, pH raised and then stabilized around 7.1. Methanogenesis was not inhibited during the 25 days of operation.

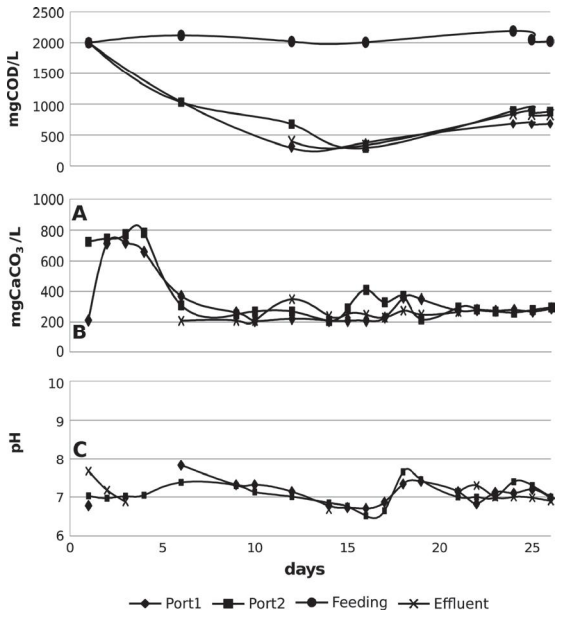

Figure 5. Results of the swine solid waste digestion test. A) Reactor temperature profile. B) COD measured at the 2 ports and the effluent. C) COD removal. D) alkalinity. E) pH.

The second control parameter was alkalinity (figure 5D). It dropped from 740 mg $CaCO_3$/L to 200 mg $CaCO_3$/L during the first 10 days. Again, values measured for ports 1 and 2 were similar, while values in the effluent were significantly lower during this period of time. After the addition of Na_2CO_3 to the feed on day 16, alkalinity rose to 400 mg $CaCO_3$/L, first at port 2 and then at port 1. For the last 15 days the alkalinity values stabilized in the three sampling points at around 300 mg $CaCO_3$/L.

Methane production was measured only during the last 3 days of operation and it was 63 mLmethane/h on average. Total biogas production was also measured after all NaOH in the gas collector was neutralized (97 mL biogas/h). Based on these results, the methane content in the biogas was 65%.

IV. DISCUSSION

The aim of this paper is to propose viable alternatives for the construction of low cost lab-scale UASB systems. It is common that lab-scale reactors are made of plexiglass, which is a relatively inexpensive material. However, we identified 3 critical aspects related to the cost of the system: heating, biogas measurement, and flow control. A cheap temperature controller costs over $ 250 dollars, while a heated bath is over $ 600 dollars, and a heated bath circulator surpasses the $ 1,500 dollars. A gas monitor surpasses the $ 3,000 dollars, while the calibration kit is over $ 600 dollars. Finally, the cheapest peristaltic pumps cost between $ 350 and $ 750 dollars (all prices as of 2015). Given those prices are prohibitive for many low-budget labs in developing countries, here we compiled several strategies to lower the price of the whole system under $ 200 dollars.

In our experience, heating of the feed before entering the reactor results problematic. Temperature decreases quickly along the UASB column (although that problem could be solved by insulation) and some COD is removed or acidified before entering the reactor, then tracking of the COD removal efficiency becomes more difficult. Alternatively, a heating jacket was tested. It resulted very efficient but its implementation requires careful attention to the potential leaking of water out of the jacket and of the content of the reactor to the jacket. Lastly, the jacket was replaced by a hose rolled around the UASB column. It works essentially as good as the jacket, but control of the leaks is considerably easier. Also, the plastic hose can be cheaply replaced, so the heating system can be kept clean effortlessly and at low cost.

A drawback of the heating system is the lack of temperature control, then temperature varies depending on the room temperature and it has to be adjusted manually, modifying the power of the heating resistance. However, the temperature variation stays in a 5°C range (approximately 2°C above and below the set temperature), which is adequate for some experiments and preliminary tests. Overall, the heating system costs approximately $ 40 dollars.

Respect to biogas collection, we adopted the liquid displacement method [12]. The first attempt consisted of connecting the biogas hose to a bottle filled with a NaOH solution. However, refilling the bottle every time it was emptied required the disconnection of the biogas collecting hose, depressurizing the reactor. This depressurization altered the hydraulic equilibrium of the reactor (as shown in figure 2, h1 defines the siphon height and the liquid level in the gravity feed tank) causing the liquid effluent to enter the gas exit.

The 3 chambers gas collector was designed to overcome this problem (figure 4). The first chamber played the role of an inverted graduated cylinder, where the gas accumulates displacing the NaOH solution to the second chamber. A purging valve permits the escape of the gas while the collecting chamber is refilled with previously displaced NaOH solution. In this case, the reactor biogas hose is never depressurized since it is permanently submerged under the liquid column in the second chamber and the reactor hydraulics is minimally altered during gas purging, avoiding the leaking of treated wastewater to the gas hose. This newly designed collector facilitates measurement of methane production many consecutive times while the UASB reactor is operated as a constant flow steady state system. Also, the neutralized NaOH can be replenished just by adding NaOH pellets directly to the solution. Overall, the cost of the plexiglass gas collector is approximately $ 30 dollars.

The third critical aspect is related to the cost of maintaining a low constant flow of wastewater to the reactor. As of 2015, cheap peristaltic pumps cost at least 350 dollars, while the average price is around 1000 dollars. This makes the pumping and flow control the most expensive component of the reactor. Replacing a peristaltic pump becomes difficult when the required wastewater flow is relatively low (in the order of a few milliliters per minute); firstly, because cheap centrifugal pumps cannot handle such low flow rates; and secondly because suspended solids in wastewater tend to obstruct hoses and valves.

The simplest tested system was just a tank connected directly to the reactor column inlet valve. Flow control in this case was highly difficult as it depended on an almost completely closed valve and the wastewater level in the feeding tank. The valve was frequently obstructed by suspended solids and the flow was constantly changing as the water head in the feeding tank decreased. Also, the only flow measurement point was the reactor discharge, so changes in liquid flow were detected a few minutes after opening or closing the valve and setting a specific flow rate was time consuming.

After several modifications, the final setup consisted of a gravity feeding tank connected to the column feeding valve and permanently fed by a submersible centrifuge pump (figure 2). As already mentioned, this pump cannot handle low flow rates, then a double valve system was implemented. A half closed ball valve acts as first

controller, lowering flow rate only partially so it does not get obstructed by suspended solids. Then a tee splits the flow, returning the most part of it to the feed reservoir tank. The second flow control point is a camber and roller clamp adapted from a venoclysis system. The roller permits fine tuning of the flow, while the transparent chamber facilitates instant checking of the flow rate by measuring time between liquid droplets. Although the enhanced system still got obstructed about once a week, its performance was good enough to run preliminary swine waste degradation experiments operating the UASB reactor as a constant flow system. Overall, the feeding system costs approximately $ 40 dollars.

The final UASB system design was operated for 25 days, achieving a quick start-up thanks to inoculation with anaerobic granular sludge. Biogas generation was registered just after 3 days of batch operation and it was maintained during 25 days of constant flow operation. The reactor was slightly acidified after 15 days of constant flow operation but daily measurement of pH and alkalinity facilitated on-time neutralization by addition of Na2CO3 to the feeding. This supports the use of these two parameters as minimal control variables for UASB operation. During the following 10 days COD removal, pH and alkalinity values stabilized and the preliminary swine waste degradation test was suspended. Methane production on days 23, 24, and 25 was on average 63 mL/h at standard temperature and pressure conditions (273.15 K and 1 atm). Considering a COD removal of 55% (1100 mgCOD/L) and a flow rate of 2 mL/min, the methane yield obtained was 0.48 mLmethane/mgCOD which is close to 0.5 mLmethane/mgCOD; a value previously reported as expected for UASB reactors [24]. This short experiment supports our low budget design as a reliable system for laboratory scale experiments

V. CONCLUSIONS

The most expensive components of a lab-scale UASB reactor were replaced by low cost substitutes. The resulting system was under 200 dollars and permitted the preliminary evaluation of a swine solid waste degradation by anaerobic digestion. A minimal control parameter scheme, consisting of pH and alkalinity measurements, was enough for avoiding acidification of the system and maintaining biogas production during 25 days of constant flow operation. We expect that this report will serve as basis for the design and construction of enhanced low cost UASB systems in other low income laboratories.

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