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Pilot-Scale Anaerobic Digestion of Pig Manure with Thermal Pretreatment: Stability Monitoring to Improve the Potential for Obtaining Methane

Marley Vanegas [1,*], Felipe Romani [1] and Mayerlenis Jiménez [2]

[1] Research Group KAÍ, Department of Chemical Engineering, Universidad del Atlántico, Puerto Colombia, Barraquilla Metropolitan Area, Barranquilla 081007, Colombia
[2] Research Group Bioprocess, Department of Chemical Engineering, Universidad del Atlántico, Puerto Colombia, Barraquilla Metropolitan Area, Barranquilla 081007, Colombia
* Correspondence: marleyvanegas@mail.uniatlantico.edu.co; Tel.: +57-605-387-66-05

Abstract: Monitoring and controlling stability in anaerobic digestion (AD) systems are essential, since it allows to obtain information that helps to take corrective actions in case of deviations in the system and to guarantee a stable performance in the biogas production. In this work, a pilot-scale CSRT reactor (1 m^3) was monitored during the anaerobic digestion of pig manure with thermal pretreatment (80 °C) operated at thermophilic temperature (45 °C). The ratio of the volatile organic acids (FOS) to the total inorganic carbonate (TAC) and the pH were the indicators used during the monitoring process to identify deviations in the AD system. Additionally, alkaline solution NaOH (98%) was applied to counteract pH deviations and maintain stability. Chemical oxygen demand (COD) and biogas composition were measured during the AD process. It was found that during the AD process, the FOS/TAC was between the range of 0.5 and 1. The results revealed that, in the anaerobic digestion of pig manure with thermal pretreatment, the pH was kept stable in the range of 6.7–7.4 since no medium acidification occurred. Additionally, the tendency of the chemical oxygen demand decreased from the 10th day of operation, product of the favorable enzymatic activity of the microorganisms, reflected in the stable production of biogas (69% CH_4). Finally, it is concluded that thermophilic AD of pig manure with thermal pretreatment is a good option when it is carried out efficiently by employing an adequate energetic integration.

Keywords: anaerobic digestion; pig manure; biogas; thermal pretreatment; monitoring stability

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1. Introduction

The continuous growth of the global economy has generated an increase in energy consumption. It is estimated that between 2012 and 2040, there will be a 48% increase in energy demand worldwide [1]. This has led to incorporating alternative energy sources to diversify the energy matrix, reduce dependence on fossil fuels and contribute to the commitments made to mitigate the effects of climate change.

Globally, biomass is a resource that is being used as a source of renewable energy generation and is expected to increase considerably in the coming years [2]. In the national context, Colombia has an estimated biomass energy potential of 61,077,778 GWh [3]. Among the biomass residues with high energy potential are sugar cane (22%), urban organic waste (18%), oil palm (21%), and pig and poultry manure (39%) [4]. In Colombia, animal manure has a low commercial value [5], and its generation is increasing due to agro-industrial activities [6]. For all the reasons mentioned above, there is a need to implement strategies oriented to its final disposal in order to reduce the high concentrations of nitrate in water and greenhouse gas emissions [7].

One of the routes to valorize animal manure and reduce its negative impact is through anaerobic digestion (AD) [8–10]. This process allows obtaining bio-energy through the degradation of different raw materials [11]. Anaerobic digestion has benefits related to reducing greenhouse gases, environmental protection, clean energy production, and the final disposal of solid waste [12].

However, despite the great potential for biogas generation from animal manure, there are still limitations in its production due to the low carbon-to-nitrogen (C/N) ratio present in manure [13]. Animal manure has total solids (TS) concentrations between 4% and 12% and volatile solids (VS) concentrations of 90% of the TS [14]. In addition, about 40–50% of VS is constituted of lignocellulosic material fibers: 30–45% cellulose, 15–40% hemicellulose, and 10–35% lignin [15]. These materials are difficult to degrade due to cellulose crystallinity and lignin interconnections within the lignocellulosic molecule [16], limiting biogas production in the hydrolysis stage [17]. Therefore, biogas production will depend on the hydraulic retention time (HRT) for disintegrating the lignocellulosic material in each feedstock source [16]. However, despite the current challenges, there is great interest in implementing alternatives to improve the yield of the anaerobic digestion process of animal manure [18].

One of the alternatives has been processes with physical pretreatment [19–21], chemical pretreatments [22–24], and biological pretreatments [25–27]. In general terms, pretreatments aim to generate changes in the composition or structure of the substrate, transforming the lignocellulosic material contained in the manure into simple soluble components that can be easily degraded during enzymatic activity. This accelerates the hydrolysis stage and reduces retention times in the bioreactor, increasing the efficiency of the system [13]. For the particular case of anaerobic digestion of pig manure, biogas production is strongly limited by the presence of lignin. As lignin values decrease, methane production increases [17].

Different authors have also studied the thermal pretreatment of swine manure. In this regard, Ferrari et al. [28] studied the effect of thermal pretreatment parameters (temperature and time) on pig manure digestion. The results indicated that thermal pretreatment improved anaerobic digestion regarding biodegradation and degradation rate. In addition, methane production efficiency was maximized at a temperature of 170 °C and 30 min. Gonzales-Fernandez et al. [29] investigated the effect of three pretreatment methods (mechanical, chemical, and thermal) on methane production from pig manure. The study revealed that thermal pretreatment showed better performance by increasing methane production (35%) and chemical oxygen demand (32%) concerning untreated samples. The study of thermo-chemical pretreatment has also shown promising results, as reported by Rafique et al. [30]. In this study, the authors found that the maximum methane production potential was obtained using thermo-chemical pretreatment at 100 °C, showing an increase of 28% over untreated samples. Finally, Carréle et al. [31] evaluated the effect of pig manure's thermal pretreatment (10–190 °C) to maximize methane production. The results showed that high temperatures (190 °C) favored manure biodegradation and increased methane production.

Although thermal pretreatments increase the efficiency of anaerobic digestion processes, it is not sufficient to evaluate the performance considering only this indicator [32]. Good process performance is achieved through adequate system stability, productivity, and efficiency. In that sense, Zhou et al. [33] investigated the biogas production from pig manure in mesophilic conditions through pH monitoring and control (pH 7–8). The authors concluded that the best biogas production and methane content is obtained at pH 7. However, the authors did not implement pretreatment to the biomass in this work. A similar study was carried out by Sun et al. [34], who monitored the anaerobic digestion process of swine manure in terms of stability indicators (pH and alkalinity) against system perturbations. However, the authors did not pretreat pig manure. Finally, Borth et al. [35] evaluated methane production from co-digestion of food and garden waste. The authors implemented an operational control for system stabilization and obtained an average specific methane yield of 0.47% L CH_4 gVS^{-1}.

Based on the above, it is evident that the pretreatment of animal manure has been a topic of great interest, as it provides a way to improve conversion efficiency and biogas production. However, studies of thermal pretreatment of pig manure have been little addressed in the scientific literature [17] and still have great opportunities to be investigated [28]. Among them is the study of the operational stability of an anaerobic digestion system using this type of pretreatment. Therefore, the main objective of this work is to evaluate the performance of an anaerobic bio-reactor under thermophilic conditions, maintaining stable conditions from a real-time operational control for the generation of biogas using pig manure with thermal pretreatment.

2. Materials and Methods

2.1. Organic Waste

The pig manure was obtained from a pig farm located in the department of Atlántico, Colombia. The physicochemical properties of the samples were total solids (TS), density, volatile suspended solids (VSS), chemical oxygen demand (COD), and alkalinity, which are listed in Table 1.

Table 1. Physicochemical properties of the analyzed sample.

TS (%)	Density (g/mL)	SSV (mg/L)	COD (mg/L)	Alkalinity (mg $CaCO_3$/L)
20.48	0.975	54.360	128.455	17.572

2.2. Methanogenic Potential and Dimensioning

Based on the physicochemical properties of the pig manure shown in Table 1, the methanogenic potential was determined to estimate digester size. Two estimation methods were used and compared with experimental data. The first was the stoichiometric estimation by degraded COD, given by Equation (1) [36]:

$$V_{CH_4} = \frac{COD_{CH_4}}{K(t)} \tag{1}$$

where V_{CH_4} is the volume of methane produced (L), COD_{CH_4} is the chemical oxygen demand (COD) removed by the bio-reactor and converted into methane (g COD) and $K(t)$ is the correction factor for the reactor operating temperature (g COD/L), calculated using Equation (2):

$$K(t) = \frac{P \cdot K}{R \cdot (273 + T)} \tag{2}$$

where P is the atmospheric pressure (1 atm), K is the COD corresponding to one mole of CH_4 (64 g COD/mol), R is the ideal gas constant (0.08206 atm. L/mol K) and T is the reactor operating temperature (°C).

The second method was Buswell's equation modified by Boyle applied to estimate the volume of the bioreactor, according to Equation (3) [37]:

$$\begin{aligned} &C_aH_bO_cN_dS_e + \left(a - \tfrac{b}{4} - \tfrac{c}{2} + \tfrac{3d}{4} + \tfrac{e}{2}\right)\cdot H_2O \\ &\to \left(\tfrac{a}{2} - \tfrac{b}{8} + \tfrac{c}{4} + \tfrac{3d}{8} + \tfrac{e}{4}\right)\cdot CO_2 + \left(\tfrac{a}{2} + \tfrac{b}{8} - \tfrac{c}{4} - \tfrac{3d}{8} - \tfrac{e}{4}\right)\cdot CH_4 + d\cdot NH_3 + e\cdot H_2S \end{aligned} \tag{3}$$

where a, b, c, d and e correspond to the percentage of each element involved in the stoichiometry. Elemental analysis was performed according to the guidelines of the ASTM standard [D 5373-16] to obtain a representative average of the percentage of each element (C, H and O). Subsequently, the results were compared with the average obtained from other bibliographic sources to complete the elemental analysis since the analysis of elements such as oxygen and sulfur was not performed. Therefore, it was necessary to validate an acceptable approximation in the values obtained from the literature [38–40]. The results are shown in Table 2.

Table 2. Ultimate analysis results and comparison.

Element	Present Work	References	Variation Coefficient (VC)
C (%)	44.28	43.81	0.7
H (%)	5.86	5.56	3.7
N (%)	3.04	3.16	2.9
O (%)	-	33.38	-
S (%)	-	0.81	-

Table 2 shows the coefficient of variation (CV) between the values obtained from the sample and the literature values. The coefficient of variation of carbon (0.7%), hydrogen (3.7%) and nitrogen (2.9%) are low. For a sample to be considered unrepresentative, it is estimated that the coefficient of variation should be close to 30%. Therefore, it is inferred that the reference values obtained from the literature are aligned with the values obtained in the laboratory, which were used in Buswell's equation, Equation (3). Based on the above, it was determined that the size of the anaerobic digestion reactor should be 0.7 m^3. By heuristics, 30% of the total volume of the bio-reactor should be available for the accumulation of the generated biogas. Therefore, the total volume of the bio-reactor was 1 m^3, as shown in Table 3.

Table 3. Bio-reactor sizing results.

Description	Value (m^3)
Estimation by COD, Equation (1)	0.777
Estimation by Buswell's equation	0.614
Average	0.695
Total volume	0.994

From the bio-reactor design, the volume of the hydrolyzer (thermal pretreatment) was determined, taking into account the substrate load to be processed to feed the bio-reactor. The substrate loading ranged from 40 L to 87.5 L. However, a volume of 40 L was selected considering the possibility of making more than one load per day according to the behavior of the system. This was done in order to not occupy the total volume of the hydrolyzer and to avoid damaging the measuring equipment inside the hydrolyzer. The active volume of the bioreactor was 700 L, with retention times between 10–20 days.

2.3. Experimental Set-Up and Pretreatment

After conditioning the raw material, it was homogenized with water up to 12% of total solids to avoid obstructions in the pipes, reduce the consumption of electrical energy in the pump associated with linear losses and guarantee uniform mixing during the pretreatment stage.

The pretreatment selected in this study was thermal. This pretreatment was carried out to eliminate pathogens that could cause inhibition in the digestion process and, in addition, to increase the soluble COD, decomposing complex and insoluble compounds into simpler compounds that are easier to degrade by bacteria [13]. The thermal pretreatment was carried out in a 70 L autoclave (hydrolyzer) equipped with an agitator (0.5 Hp, double impeller), as shown in Figure 1. The hydrolyzer was composed of ① serpentine, ② tubular burners, ③ electrical resistance heating, ④ accessories couplings, ⑤ discharge couplings and ⑥ insulation jacket. The electrical resistance heating allowed the substrate heating process to be carried out for 30 min at 80 °C [31,41]. Additionally, the substrate was cooled until the operating temperature of the bio-reactor (thermophilic regime, 45 °C) by flowing cooling water through the serpentine. The heat gained by the water was stored in insulated tanks for later be used in the bio-reactor according to its thermal requirements. In this way, the process was carried out efficiently, and the electrical energy consumption was reduced.

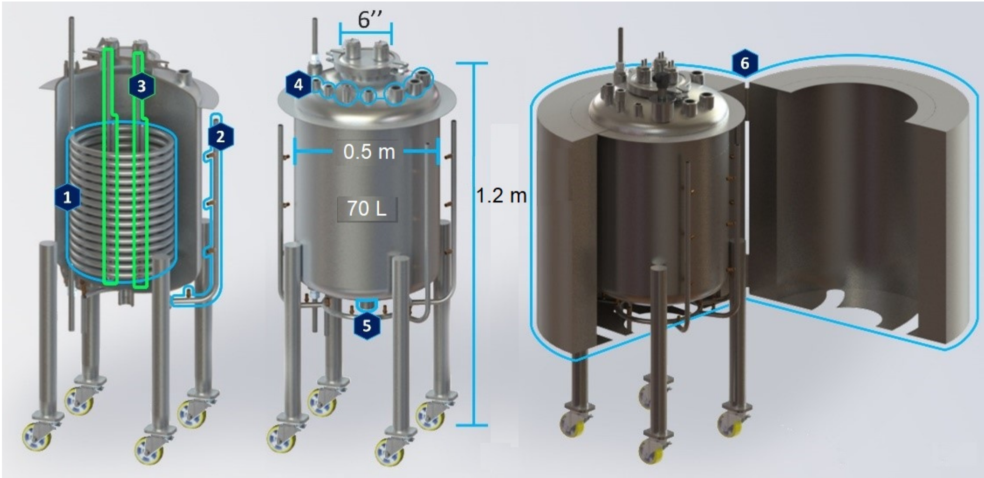

Figure 1. Experimental schematic of the hydrolyzer.

After the cooling process, the substrate is pumped into the bio-reactor. The anaerobic digestion process was carried out in a 1 m^3 stainless steel bio-reactor with a jacket for heating, as shown in Figure 2.

Figure 2. Experimental schematic of the bio-reactor.

The bio-reactor consisted of ① a washing and maintenance manhole, ② top cover couplings, ③ thermal jacket couplings, ④ additional couplings, ⑤ tank discharge couplings, ⑥ a thermal jacket, ⑦ fiberglass insulation and ⑧ a float level sensor. The bioreactor incorporated significant design changes from traditional technologies. Among them is the possibility of operating at pressures around 200 psig, reducing the system's volume. In addition, the thermal jacket in the bio-reactor made it possible to take advantage of part of the heat coming from the hydrolyzer, maintaining a thermophilic regime with controlled and constant temperature, favoring the growth of the bacterial consortium and increasing the production rate [42]. The agitation process was carried out by regurgitation through a peristaltic pump (1 Hp) with a flow rate of 5 L/min. In addition, an automatic control system (Simatic S7-1200, Siemens, Beijing, China) was installed in the bio-reactor to measure, monitor and control the temperature. This variable was controlled by means of a P&ID control loop to maintain the thermophilic regime (45 °C) by passing hot water from the storage tank through the bio-reactor jacket. The internal pressure did not exceed 200 psig and was regulated by a solenoid valve that released part of the gas contained in the bio-reactor.

2.4. Analytical Methods

The substrate was characterized throughout the digestion using an analyzer (Titralab AT1000, Hach Lange GmbH, Düsseldorf, Germany,) with samples of 200 mL. The concentration of volatile organic acids (FOS mg CH_3COOH/L), total inorganic carbonate (TAC mg $CaCO_3$/L) and the FOS/TAC ratio were determined. A pH-meter measured the pH for semi-solid samples (PH60S premium pH-meter, Apera Instruments, Columbus, OH, USA). Hach's COD digestion vials (high range) without mercury (range: 20–1500 mg/L COD) and a spectrophotometer (DR6000 hach, Hach Lange GmbH, Düsseldorf, Germany) were used to determine the chemical oxygen demand (COD). 2 mL of the previously diluted sample together with the reagent were introduced into the vials. The vials were placed in a thermoreactor, where they were left to react for 2 h at 150 °C. Finally, the sample was cooled, and the measurement was performed with the help of the spectrophotometer. The gas quality was measured by means of a Biogas analyzer (Biogas5000, Envirotecnics, Girona, España), where the gas composition was determined: CH_4 (% vol), CO_2 (% vol), O_2 (% vol), NH_3 (ppm), H_2S (ppm) and balance (% vol). These measurements were taken daily to monitor the performance of the process.

2.5. Parameter Monitoring and Stabilization

The bioreactor was operated for 60 days, with hydraulic retention times (HRT) of 17 days. In addition, to guarantee and maintain good conversion efficiencies, it was necessary to monitor and control the pH daily to guarantee the system's stability [43]. The substrate pH was stabilized between 6.5–7.4 by adding $NaOH$ (98%) to achieve the basicity of the medium. $NaOH$ addition was between 0.25–0.5 g $NaOH$/L substrate day.

3. Results and Discussion

3.1. System Stability: Variation of pH and FOS/TAC during Processing

The start-up stage of the bio-reactor is a critical stage during the digestion process [44]. Therefore, its stabilization during the experiment time against the fluctuations of variables such as temperature and pH was of great importance.

The inoculum (pig manure) came from 12 L and 45 L bio-reactors located in the same laboratory, where it was cultured at 45 °C for 20 days prior to digestion. The initial load in the bio-reactor was 143 L (60% substrate, 40% inoculum) with a pH of 7.01 and a concentration of 12% total solids. Figure 3 shows the pH and FOS/TAC ratio variation during the digestion process. As for pH, it was carefully monitored, and its values were adjusted by adding buffer solution (alkaline reagents) to the organic substrate loads, since conversion yields depend significantly on an adequate pH regulation [43].

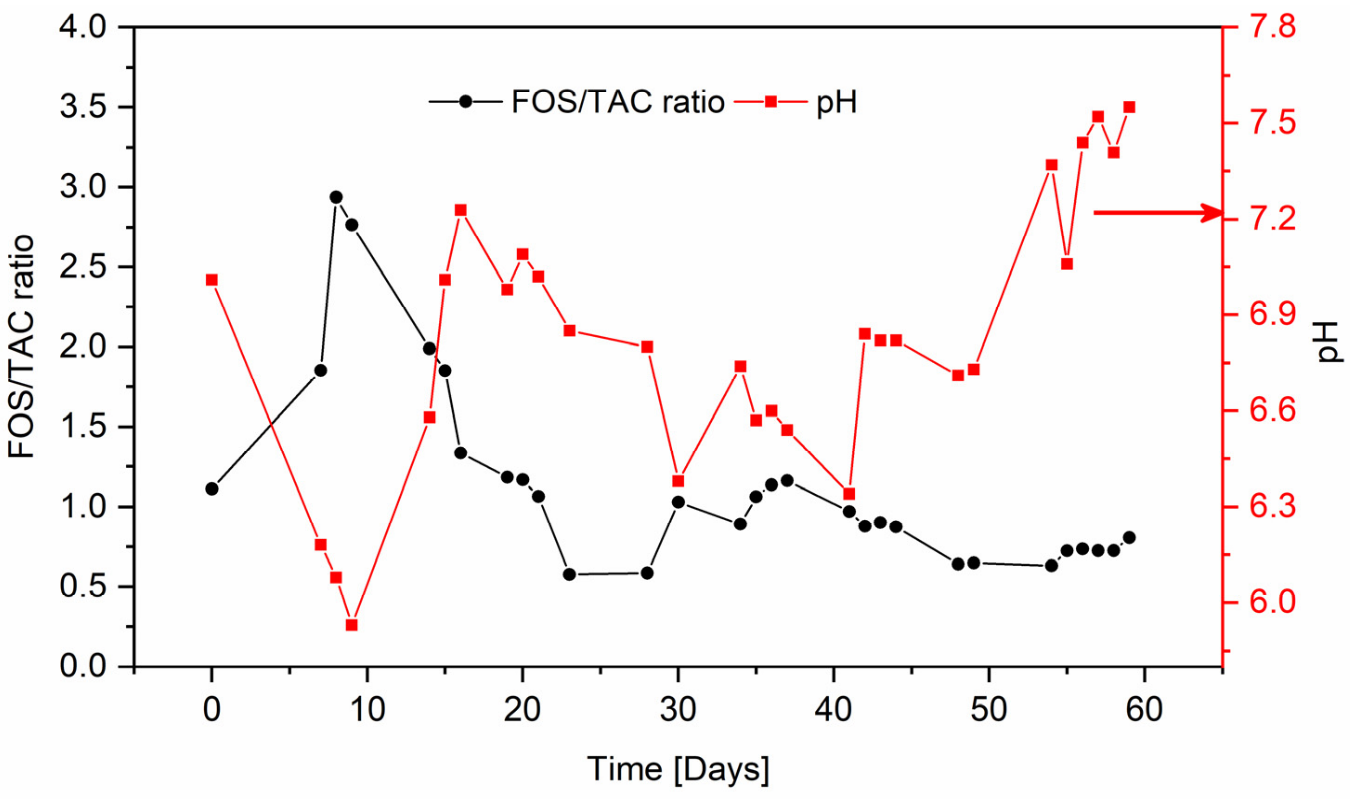

Figure 3. Variation of pH and FOS/TAC ratio during the AD.

Initially, a substantial reduction in pH from 7.2 (day 0) to 6.2 (day 7) is observed. This behavior could be associated with the accumulation of short-chain fatty acids (SCFAs) resulting from the enzymatic activity of the microorganisms in the hydrolytic stage [14]. The high accumulation of SCFAS in the thermophilic digestion of pig manure after the starter stage can be attributed to the uncoupling between the three main microbial groups involved in organic matter degradation [44]. From the 10th day, an increase in pH is observed due to the addition of *NaOH*, which caused a neutralization of the SCFAS in order to stabilize the system. However, a slight decrease in the pH is observed between the 15th day and the 40th day. This decrease could also be attributed to an excessive accumulation of fatty acids [14]. High consumption in the system's alkalinity can contribute to a reduction in the system's pH [45]. Therefore, adding a buffer solution was necessary to counteract this behavior. As a result, throughout the digestion process, the addition of alkaline reagents (*NaOH*) was necessary for substrate loads with basic pH (pH = 8).

Alkaline reagents prevent pH decrease during the acidogenesis stage, increasing efficiency in the methanogenesis stage [46]. Thus, an optimum pH range was maintained for the enzymatic activity of the microorganisms involved in the process, producing stability in the system. This was reflected in an increase in pH (Figure 3) and the stable methane concentration (Figure 4a) as of day 30. Furthermore, the addition of alkaline agents allowed the neutralization of the acids and, as a result, the stabilization of the system. This result is in line with that reported by Zhou et al. [33], who evaluated the performance of biogas production using pig manure under neutral conditions at mesophilic regime. The results showed that the highest methane concentration was obtained at pH 7.

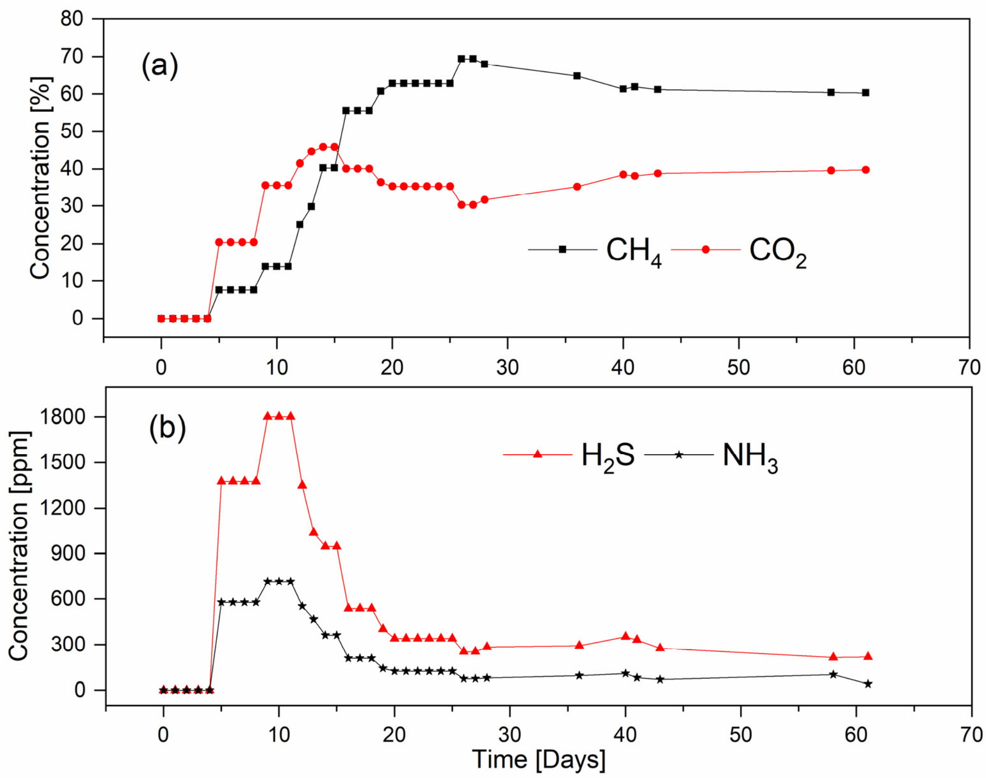

Figure 4. Variation of gas quality during digestion: (**a**) CH_4 and CO_2 concentrations; (**b**) H_2S and NH_3 concentrations.

In general terms, it can be inferred that the pH remained in the range of 6.7–7.4, indicating that the system operated in a normal state without the risk of acidification. In this interval, the average pH was 6.9, which is within the range for anaerobic digestion processes, as reported in the literature [13]. It is pertinent to emphasize that both methanogenic and acidogenic microorganisms have optimum pH levels for their activity. Methanogenesis is efficient, with pH values between 6.5 and 8.2 [47], whereas acidogenesis has pH values between 5.5 and 6.5 [48]. In this sense, the results suggest that the pH range maintained during pig manure digestion was favorable for the methanogenic and acidogenic stages at thermophilic temperature.

Although monitoring and control of pH throughout the process prevented acidification of the medium, some authors [49,50] have reported that this parameter is insufficient to understand and analyze the system's stability. The FOS/TAC ratio is an indicator that allows for determining the ratio between the volatile organic acids present (FOS) and the total inorganic carbonate (TAC). This indicator allows corrective actions to be taken in case of deviations in its values to guarantee the stability of the digester. Studies have reported optimal FOS/TAC ratio ranges between 0.3 and 0.4 as a measure of the stability of the digestion process. Values of FOS/TAC greater than 0.4 indicate that the digester is overfed, whereas values less than 0.3 indicate a lack of substrate in the digester [32]. However, each system can handle different intervals according to the preferences in the adaptation processes of the microorganisms.

Figure 3 shows that, in the first ten days (adaptation phase), the FOS/TAC ratio increased from 1.1 to 2.7, indicating the accumulation of volatile fatty acids (VFAs) in the bio-digester, which was evidenced by a reduction in the pH. In order to stabilize the system, adding substrate with alkaline reagents was necessary to improve stability. The addition of organic substrate loads allowed an adequate operation of the digester, guaranteeing neutrality in the medium. From the 20th day, a reduction in the FOS/TAC ratio was observed, whose average value was 0.8. As mentioned above, the FOS/TAC value can increase or decrease depending on the adaptation preferences of the microorganisms. For thermophilic anaerobic digestion of pig manure, the results indicate that the digester can operate stably with a FOS/TAC ratio between 0.5 and 1.

3.2. Biogas Concentration Variation during AD

The performance of an anaerobic digestion process can be evaluated in terms of stability (pH, FOS/TAC), productivity, and efficiency [32]. The effect of adequate system stability can be reflected in its productivity, i.e., in biogas quality.

The effect of system stabilization was evidenced by the constant production of good-quality biogas, as shown in Figure 4. Initially, high hydrogen sulfide and ammonia concentrations were observed (Figure 4b). However, as the process continued, their concentrations decreased as a result of the biogas purges in the system. As a result, methane and carbon dioxide concentrations increased to almost constant levels (Figure 4a). These results suggest that it is possible to maintain biogas production in a stable condition.

Additionally, the results show that, from the 15th day of digestion, the methane concentration in the biogas was higher than 55%, reaching levels close to 70% at the end of the process. However, these values differ from Zhou et al. [33], who reported a methane concentration of no more than 55% during the digestion of pig manure at mesophilic regime. The difference in concentrations could be attributed mainly to the operating regime of the system. That is, the thermophilic regime favored the increase in methane concentration with respect to the mesophilic regime, which can be considered an advantage. On the other hand, the effect of the thermal pretreatment of the pig manure in this study could also affect methane production.

Pig manure is characterized by its high content of lignocellulosic material fibers [15] difficult to biodegrade during enzymatic activity, limiting the production of biogas in the hydrolysis stage [17]. Therefore, the thermal pretreatment process could have produced changes in the composition or structure of the substrate, transforming the lignocellulosic material contained in the manure into simple soluble components that can be easily degraded during enzymatic activity [13], increasing the chemical oxygen demand (COD) levels and increasing the yield of the system [13]. In this regard, Rafique et al. [30] reported that thermal pretreatment (25–150 °C) of pig manure improved digestion in terms of biogas (28%) and methane production (25%) with respect to untreated samples. Similar results were obtained by Carrère et al. [31], who reported that thermal pretreatment of pig manure increased manure biodegradation and had a positive effect on methane potential. Therefore, the results of this study suggest a positive effect in terms of biogas composition resulting from the thermal pretreatment and the adequate stabilization of the digester during the process, since there was no acidification of the medium.

On the other hand, although the thermophilic regime is often considered an unattractive option because of the energy consumption [13], the results of this study indicate that good results can be obtained when a correct energetic integration is carried out to take advantage of the heat from the thermal pretreatment process to be used later in the digester to maintain the thermophilic regime. Additionally, some authors [51] have found that, in the thermophilic digestion of manure, it is not possible to achieve system stability as a result of the accumulation/degradation of long-chain volatile acids (LCVA). However, the results of this work indicate that it is possible to achieve stable bio-reactor operation by monitoring and controlling system variables.

3.3. Variation of COD during Processing

The variation of the chemical oxygen demand (COD) during the digestion process is shown in Figure 5. On the 10th day of operation, a high concentration of COD is observed; this could be attributed to the enzymatic hydrolytic activity of the microorganisms (adaptation phase). Usually, in this first stage, there is a high organic load in the reactor and little variation in the COD [43]. Additionally, according to Lu et al. [52], in the acidogenesis stage, COD is low because the substrate is converted into products such as alcohols and volatile fatty acids (VFAs); therefore, the COD concentration is maintained. In addition, the loss in COD is due to the formation of gases such as H_2 and CO_2. However, from the 10th day onwards, COD decreases until the end of the process.

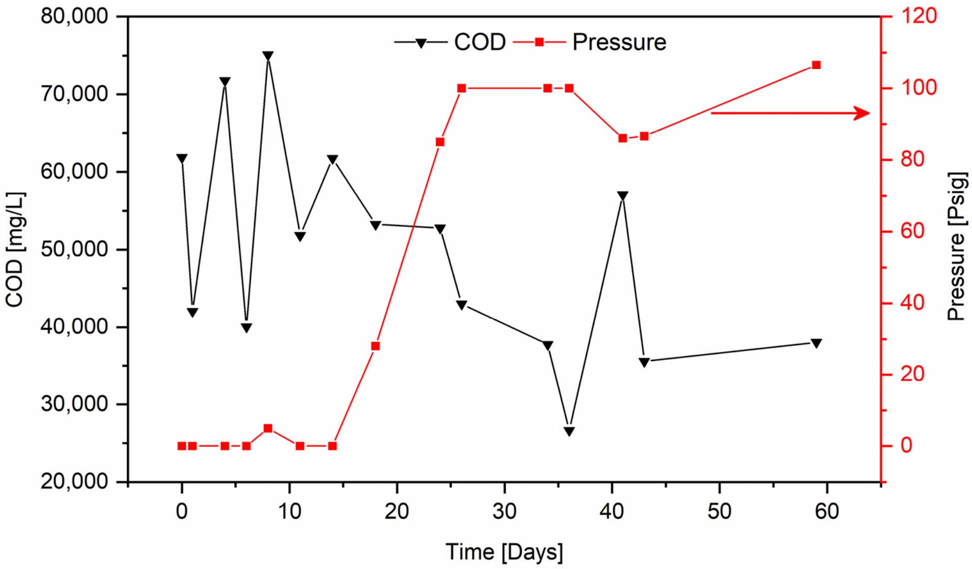

Figure 5. Variation of COD and pressure during digestion.

This behavior can be associated with the degradation of the substrate by the methanogenic bacteria, which is reflected in an increase in pressure and better biogas quality (Figure 4) [43]. The COD reduction could result from a stable pig manure digestion operation, which is congruent with that reported by Chuenchart et al. [32]. This result is evidenced in the biogas composition shown in Figure 4a, where it is observed that the reduction in COD favored the formation of methane in the system. Finally, the chemical demand peaks found, for example, on the 40th day of operation, are due to the organic load supplied to the system.

4. Conclusions

Monitoring and controlling stability in anaerobic digestion (AD) systems are essential to guarantee a good performance in biogas production. It is concluded that it is possible to perform anaerobic digestion of pig manure with thermal pretreatment in a stable way with a pH between 6.7–7.4. Additionally, the results showed that the FOS/TAC ratio of pig manure was between the range of 0.5 and 1. It is concluded that accurate monitoring and control of the system's stability allows a stable biogas production (69% CH_4) with good acidification control. Finally, it is concluded that the AD of pig manure at thermophilic temperature with thermal pretreatment is a good option when it is carried out efficiently by utilizing an adequate energetic integration.

Finally, it is concluded that the results of this research provide the basis for further exploration of the stability of biogas generation for its subsequent scaling up. In addition, it contributes to the country's commitment to implementing new biogas generation technologies at the laboratory level. However, future studies oriented towards the thermo-economic and environmental evaluation of this system that includes the coupling to energy generation systems (microturbines or internal combustion engines) should be taken into account. In this way, it provides a reference framework in economic, technical and environmental terms to evaluate the profitability of electric power generation projects from alternative sources (biogas). In this way, it contributes to closing gaps in the Colombian energy market related to the low participation of alternative energy sources, and the commitments acquired in terms of energy transition and the reduction of greenhouse gases.

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Nomenclatures

AD	Anaerobic digestion
SCFAs	Short-chain fatty acids
BMP	Biochemical methane potential
COD	Chemical oxygen demand (mg/L)
FOS	Volatile organic acids (mg/L)
TAC	Total inorganic carbon (mg/L)
LCFAs	Long-chain fatty acids
TAN	Total ammonia nitrogen (mg/L)
TS	Total Solids (mg/L)
VS	Volatile solids (mg/L)
VSS	Volatile suspended solids (mg/L)
VFAs	Volatile fatty acids

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