Study of the influence of the physicochemical and operational parameters considered in anaerobic digestion models on the performance and quality of biogas production processes: A Review

Estudio de la influencia de los parámetros fisicoquímicos y operacionales considerados en los modelos de digestión anaerobia sobre el rendimiento y calidad de los procesos de obtención de biogás: una revisión

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ABSTRACT

Considering the high rates of atmospheric pollution caused by the exploitation of fossil fuels on planet Earth, the generation of new, affordable, and economical alternative fuels to minimize this problem is a widely studied initiative. Biogas production from organic matter represents one of the most promising initiatives in this field. For this reason, this publication presents a study of the influence of the physicochemical and operational parameters considered in the anaerobic digestion models, which study the yield and quality of the biogas obtained by route. The operating parameters analyzed from the scientific literature such as temperature, pH, hydraulic retention time, carbon/nitrogen ratio, among others, can be used to perform comparisons between different techniques, which allows varying raw materials, establishing operating conditions, and scaling processes. The results indicate that there are different types of substrates, which are associated with considerable yield percentages; as is the case of pig and cattle manure, carbon/nitrogen ratios were established according to the raw material and the most important reactions of anaerobic digestion. The data of the review were compared with those obtained in the laboratory of transformation of organic materials of the Universidad del Atlántico, thus obtaining a great similarity in most of the reported data.

Keywords: *Parameters, substrate; co-digestion; anaerobic digestion; simulation;review; biogas.*

RESUMEN

Teniendo en cuenta los altos índices de contaminación de la atmósfera por la explotación de combustibles fósiles en el planeta tierra, la generación de nuevos combustibles alternativos, asequibles y económicos que permitan minimizar esta problemática, es una de las iniciativas que se vienen estudiando ampliamente a nivel mundial. La producción de biogás a partir de materia orgánica representa una de las iniciativas más prometedoras en este campo. Por tal razón, esta publicación presenta un estudio de la influencia de los parámetros fisicoquímicos y operacionales considerados en los modelos de digestión anaerobia, que estudian el rendimiento y calidad del biogás obtenido por esta vía. Los parámetros de operación analizados de la literatura científica como la temperatura, el pH, el tiempo de retención hidráulico, la relación carbono/nitrógeno, entre otros, se pueden utilizar para realizar comparaciones entre diferentes técnicas, lo que permite variar materias primas, establecer condiciones de operación y escalar procesos. Los resultados obtenidos indican que existen diferentes tipos de sustratos, los cuales están asociados a porcentajes de rendimientos considerables, como es el caso del estiércol de cerdo y el vacuno, se establecieron las relaciones carbono/nitrógeno según la materia prima y las reacciones más importantes de la digestión anaerobia. Se confrontaron los datos de la revisión con los obtenidos en el laboratorio de transformación de materiales orgánicos de la Universidad del Atlántico, obteniéndose así una gran similitud en la mayoría de los datos reportados.

Palabras clave: Parámetros, sustrato, co-digestión, digestión anaeróbica, simulación, revisión, biogás

1. INTRODUCTION

The biggest problem facing humanity today is climate change. The effect this is having on global temperature has been observed in recent years and will continue to increase, affecting ecosystems, wildlife, levels of the organization, and the world population [1], [2]. In recent decades, many organizations have warned about this phenomenon, which is mainly due to anthropogenic emissions of greenhouse gases, which are caused by the production of energy from fossil fuels [2], [3], [4] representing 77% of the world’s energy comes from this source [5].

In this sense, biomass energy is considered one of the most prominent renewable energy sources, together with solar energy and wind energy, as an alternative to mitigate the problem associated with pollution and global warming [6], [7].

Biomass is a raw material in biogas production through anaerobic digestion processes [8]. Comparing this non-conventional source of energy with other renewable energy sources, it is highlighted that it can be easily transported and stored, and it can be used to produce heat and electricity [9], [10]. In addition, biogas can be used to power vehicles and can be transported through gas networks [11]. Biogas production is very much in line with the circular bio-economy, which can help to manage biomass resources with greater engagement [12].

Various types of biomass can be used in biogas production, such as wheat straw, corn stover, sugar cane bagasse, forest residues, switchgrass, energy cane, sorghum, food waste, sewage sludge, livestock waste, manure, municipal waste sorted at source and wastewater with a high organic content [13], [14]. This makes it possible to diversify the raw material possibilities in energy production according to where these wastes are generated and the quantity available.

On the other hand, gross final energy consumption as a proportion of energy from renewable sources reached 19.73% in the European Union [15]. Globally, total final energy consumption from renewable sources was also on the rise and reached 10.6% (with 4% thermal energy, 3.6% - hydroelectric, 2% - wind and solar energy, and 1% - transportation biofuels). While nuclear energy and fossil fuels accounted for 2.2% and 79.7%, respectively; the remaining 7.5% of total final energy consumption was biomass [16].

In Colombia, hydroelectric power accounts for 69.77% of total energy generation, followed by gas (10.08%) and coal (8.15%). Within the non-conventional renewable energies, the participation of wind power stands out with 0.11%, solar with 0.06%, bagasse with 0.78%, and biogas with 0.02% [17].

By 2020, the International Energy Agency published a report pointing out the enormous untapped potential of sustainable biomass for clean energy production. However, although small-scale biogas plants have been implemented worldwide, only a few are in use due to insufficient knowledge of anaerobic digestion and inadequate potential of installed plants [6].

However, biogas production is not straightforward since plant operation maintenance and investment costs are considered critical factors. One way to improve biogas production technology is to study the mechanisms through which the process is carried out using the data reported in the scientific or experimental literature [18].

For the reasons described above, the main objective of this article is to study the influence of the physicochemical and operational parameters considered in the anaerobic digestion models on the performance and quality of the biogas production process.

2. METHODOLOGY

It is pertinent to emphasize that the technology for obtaining biogas is not new and that many works have been developed highlighting its benefits. Therefore, it is necessary to search the scientific literature to review the advances made in biogas production, taking into account the critical parameters according to the working conditions of each system. This allows to contrast them with experimental data obtained from laboratory tests to evaluate the influence of these parameters on the performance and quality of the anaerobic digestion process.

Scientific Literature Data

Initially, a data search was carried out in the scientific literature, including journals, books, websites, and databases, among others, in order to find the parameters commonly used to carry out the anaerobic digestion process and thus the generation of biogas from organic waste.

The topic's relationship with the research's central objective was considered in the search and selection of articles, theses, books, or other files of interest. All those documents related to anaerobic digestion or biogas production were selected.

Approximately 200 documents were examined, of which 80 files were pre-selected and reviewed. After this review, only 55 documents containing information of interest to the central theme of the research were selected.

The criteria taken into account for the selection of the last 55 documents were as follows:

- ✓ The documents were published from 2010.
- ✓ The documents mentioned some type of raw material used in biogas production.
- ✓ The documents mentioned the number of reactions that occur in the process.
- ✓ The documents mention the different stages in which the biogas production process is carried out.
- ✓ The documents will identify the temperature and pH ranges in which the microorganisms can develop.

- ✓ The documents will specify parameters related to the degree of agitation, total solids, hydraulic retention time (HRT), and the most important bacterial consortia, among others of interest for the development of the work.

Then, they were tabulated according to the similarity or relationship in their parameters.

Experimental Data

An anaerobic digester prototype was developed in the organic materials transformation laboratory at the Universidad del Atlántico. In this prototype, a series of experimental runs were carried out, which yielded a set of data (see figure 1).

The biodigester was built in stainless steel with a volume of 1 m^3, of which 0,7 m^3 is available for biomass loading and 0,3 m^3 for biogas production, covered by a jacket to maintain the temperature range depending on the heat treatment. On the other hand, it has a washing and maintenance inlet, a series of couplings for the reactor and for the jacket (inlets and outlets), fiberglass insulation and has a series of level, pressure and temperature sensors incorporated. It presents a system of agitation by regurgitation through a peristaltic pump [19].

After tabulating the data, both from the literature review (see tables 3 to 15) and the experimental data (see tables 17 and 18), they were contrasted to establish how far apart they were from each other, and which parameters were reported in the literature that were not among those reported in the laboratory or vice versa.

Figura 1. Biodigestor construido para el aprovechamiento de materias primas orgánicas.
Figure 1. Biodigester built for the utilization of organic raw materials.

3. RESULT AND DISCUSSION

Data from scientific literature

Reactions

In anaerobic digestion, multiple reactions are carried out, making it difficult to study. Therefore, the most reported by the authors in the scientific literature were taken. They were divided into two types of reactions: stoichiometric and kinetic.

Stoichiometric reactions are carried out in the hydrolysis stage and use the conversion fractions of the reactants [20], as shown in Table 1, where the different reactions and the conversion percentages of each one are shown.

Tabla 1. Reacciones estequiométricas de hidrólisis.
Table 1: Stoichiometric hydrolysis reactions [21], [22], [23].

No	Component	Hydrolysis reaction	% Conversions
1	Starch	$(C_6H_{12}O_6)_n + H_2O \rightarrow nC_6H_{12}O_6$	$0,6 \pm 0,2$
2	Cellulose	$(C_6H_{12}O_6)_n + H_2O \rightarrow nC_6H_{12}O_6$	$0,4 \pm 0,1$
3	Hemicellulose	$C_5H_8O_4 + H_2O \rightarrow 2,5C_2H_4O_2$	$0,4 \pm 0,0$
4	Hemicellulose	$C_5H_8O_4 + H_2O \rightarrow C_2H_{10}O_5$	$0,6 \pm 0,0$
5	Xylose	$C_5H_{10}O_5 \rightarrow C_2H_4O_2 + 3H_2O$	$0,6 \pm 0,0$
6	Cellulose	$C_6H_{12}O_6 + H_2O \rightarrow 2C_2H_6O + 2CO_2$	$0,4 \pm 0,1$
7	Ethanol	$2C_2H_6O + CO_2 \rightarrow 2C_2H_4O_2 + CH_4$	$0,6 \pm 0,1$
8	Soluble Protein	$C_{13}H_{25}O_7N_3S + 6H_2O \rightarrow 6,5CO_2 + 6,5CH_4 + 3NH_3 + H_2S$	$0,5 \pm 0,2$
9	Insoluble protein (IP)	$PI + 0,3337H_2O \rightarrow 0,045C_6H_{14}N_4O_2 + 0,048C_4H_7NO_4 + 0,047C_4H_9NO_3 + 0,172C_3H_7NO_3 + 0,074C_5H_9NO_4 + 0,111C_5H_9NO_2 + 0,25C_2H_5NO_2 + 0,047C_3H_7NO_2 + 0,067C_3H_6NO_2S + 0,074C_5H_{11}NO_2 + 0,07C_6H_{13}NO_2 + 0,046C_6H_{13}NO_2 + 0,036C_9H_{11}NO_2$	$0,6 \pm 0,1$
10	Triolein	$C_{57}H_{104}O_6 + 3H_2O \rightarrow C_3H_8O_3 + 3C_{18}H_{34}O_2$	$0,5 \pm 0,2$
11	Tripalmate	$C_{51}H_{98}O_6 + 8,436H_2O \rightarrow 4C_3H_8O_3 + 2,43C_{16}H_{34}O$	$0,5 \pm 0,3$
12	Palmitoyl-Olein	$C_{37}H_{70}O_5 + 4,1H_2O \rightarrow 2,1C_3H_8O_3 + 0,9C_{16}H_{34}O + 0,9C_{18}H_{34}O_2$	$0,6 \pm 0,2$
13	Palmitoyl-Linolein	$C_{37}H_{68}O_5 + 4,1H_2O \rightarrow 2,2C_3H_8O_3 + 0,9C_{16}H_{34}O + 0,9C_{18}H_{34}O_2$	$0,6 \pm 0,2$

Tabla 2. Reacciones cinéticas de los aminoácidos y las etapas acidogénicas, acetogénicas y metanogénicas.
Table 2: Kinetic reactions of amino acids and the acidogenic, acetogenic, and methanogenic stages [23].

N°	Components	Chemical Reactions	Kinetics Constants g/L
		Amino Acid Degradation Reactions	
1	Glycine	$C_2H_5NO_2 + H_2 \rightarrow C_2H_4O_2 + NH_3$	1.28×10^{-2}
2	Teronin	$C_4H_9NO_3 + H_2 \rightarrow C_2H_4O_2 + 0,5C_4H_8O_2 + NH_3$	1.28×10^{-2}
3	Histidine	$C_6H_8N_3O_2 + 4H_2O + 0,5H_2 \rightarrow CH_3NO + C_2H_4O_2 + 0,5C_5H_{10}O_2 + 2NH_3 + CO_2$	1.28×10^{-2}
4	Arginine	$C_6H_{14}N_4O + 3H_2O + H_2 \rightarrow 0,5C_2H_4O_2 + 0,5C_3H_6O_2 + 0,5C_5H_{10}O_2 + 4NH_3 + CO_2$	1.28×10^{-2}
5	Proline	$C_5H_9NO_2 + H_2O + H_2 \rightarrow 0,5C_2H_4O + 0,5C_3H_6O_2 + 0,5C_5H_{10}O_2 + NH_3$	1.28×10^{-2}
6	Methionine	$C_5H_{11}NO_2S + 2H_2O \rightarrow C_3H_6O_2 + CO_2 + NH_3 + H_2 + CH_4S$	1.28×10^{-2}
7	Aspartic Acid	$C_4H_7NO_4 + 2H_2O \rightarrow C_2H_4O_2 + 2CO_2 + NH_3 + 2H_2$	1.28×10^{-2}
8	Glutamic Acid	$C_5H_9NO_4 + H_2O \rightarrow C_2H_4O_2 + 0,5C_4H_8O_2 + NH_3 + CO_2$	1.28×10^{-2}
9	Histidine	$C_6H_8N_3O_2 + 5H_2O \rightarrow CH_3NO + 2C_2H_4O_2 + 2NH_3 + CO_2 + 0,5H_2$	1.28×10^{-2}
10	Arginine	$C_6H_{14}N_4O_2 + 6H_2O \rightarrow 2C_3H_4O_2 + 4NH_3 + 2CO_2 + 3H_2$	1.28×10^{-2}
11	Lysine	$C_6H_{14}N_2O_2 + 2H_2O \rightarrow C_2H_4O_2 + C_4H_8O_2 + 2NH_3$	1.28×10^{-2}
12	Leucine	$C_6H_{13}NO_2 + 2H_2O \rightarrow C_5H_{10}O_2 + NH_3 + CO_2 + 2H_2$	1.28×10^{-2}
13	Isoleucine	$C_6H_{13}NO_2 + 2H_2O \rightarrow C_5H_{10}O_2 + NH_3 + CO_2 + 2H_2$	1.28×10^{-2}
14	Phenylalanine	$C_9H_{11}NO_2 + 2H_2O \rightarrow C_6H_6 + C_2H_4O_2 + NH_3 + CO_2 + H_2$	1.28×10^{-2}
15	Tyrosine	$C_9H_{11}NO_3 + 2H_2O \rightarrow C_6H_6O + C_2H_4O_2 + NH_3 + CO_2 + H_2$	1.28×10^{-2}
16	Glycine	$C_2H_5NO_2 + 0,5H_2O \rightarrow 0,75C_2H_4O_2 + NH_3 + 0,5CO_2$	1.28×10^{-2}
17	Alanine	$C_3H_7NO_2 + 2H_2O \rightarrow C_2H_4O_2 + NH_3 + CO_2 + 2H_2$	1.28×10^{-2}
18	Cysteine	$C_3H_6NO_2S + 2H_2O \rightarrow C_2H_4O_2 + NH_3 + CO_2 + 0,5H_2 + H_2S$	1.28×10^{-2}
		Acidogenic reactions	

19	Dextrose	$C_6H_{12}O_6 + 0{,}1115NH_3 \rightarrow 0{,}1115C_5H_7NO_2 + 0{,}744C_2H_4O_2 + 0{,}5C_3H_6O_2 + 0{,}4409C_4H_8O_2 + 0{,}6909CO_2 + 1{,}0254H_2O$	9.54×10^{-3}
20	Glycerol	$C_3H_8O_3 + 0{,}4071NH_3 + 0{,}0291CO_2 + 0{,}0005H_2 \rightarrow 0{,}04071C_5H_7NO_2 + 0{,}94185C_3H_6O_2 + 1{,}09308H_2O$	1.01×10^{-2}
	Acetogenic reactions		
21	Oleic Acid	$C_{18}H_{34}O_2 + 15{,}2396H_2O + 0{,}2501CO_2 + 0{,}1701NH_3 \rightarrow 0{,}1701C_5H_7NO_2 + 8{,}6998C_3H_4O_2 + 14{,}4978H_2$	3.64×10^{-12}
22	Propionic Acid	$C_3H_6O_2 + 0{,}06198NH_3 + 0{,}31433H_2O \rightarrow 0{,}06198C_5H_7NO_2 + 0{,}9345C_2H_4O_2 + 0{,}660412CH_4 + 0{,}160688CO_2 + 0{,}0005H_2$	1.95×10^{-7}
23	Isobutyric Acid	$C_4H_8O_2 + 0{,}0653NH_3 + 0{,}8038H_2O + 0{,}5543CO_2 + 0{,}0006H_2 \rightarrow 0{,}0653C_5H_7NO_2 + 1{,}8909C_2H_4O_2 + 0{,}446CH_4$	5.88×10^{-6}
24	Isovaleric Acid	$C_5H_{10}O_2 + 0{,}0653NH_3 + 0{,}5543CO_2 + 0{,}8044H_20 \rightarrow 0{,}0653C_5H_7NO_2 + 0{,}8912C_2H_4O_2 + C_3H_6O_2 + 0{,}4454CH_4 + 0{,}0006H_2$	3.01×10^{-8}
25	Linoleic Acid	$C_{18}H_{32}O_2 + 15{,}356H_2O + 0{,}482CO_2 + 0{,}1701NH_3 \rightarrow 0{,}1701C_5H_7NO_2 + 8{,}4402C_2H_4O_2 + 14{,}9748H_2$	3.64×10^{-12}
26	Palmitic Acid	$C_{16}H_{34}O + 15{,}253H_2O + 0{,}482CO_2 + 0{,}1701NH_3 \rightarrow 0{,}1701C_5H_7NO_2 + 8{,}4402C_2H_4O_2 + 14{,}9748H_2$	3.64×10^{-12}
	Methanogenic reactions		
27	Acetic acid	$C_2H_4O_2 + 0{,}022NH_3 \rightarrow 0{,}022C_5H_7NO_2 + 0{,}945CH_4 + 0{,}066H_20 + 0{,}945CO_2$	3.39×10^{-3}
28	Hydrogen	$14{,}4976H_2 + 3{,}8334CO_2 + 0{,}0836NH_3 \rightarrow 0{,}0836C_5H_7NO_2 + 3{,}4154CH_4 + 7{,}4996H_20$	3.39×10^{-3}

According to Table 1, the formation of sugars, fatty acids, and alcohols are considered stoichiometric reactions where the reaction's kinetics is irrelevant. The products at this stage depend on a conversion fraction for the reactants [23].

The development of the subsequent stages of anaerobic digestion: acidogenesis, acetogenesis, and methanogenesis, depend on the kinetics of the reactions [24]. The ADM1 model (Anaerobic Digestion Model No. 1) can be established as a sub-model of the Process Simulation Model (MSP) proposed by [20] to determine the kinetics of each of them. The ADM1 is a universally applicable kinetic model that allows the mathematical description of the anaerobic digestion of different types of organic substrates, in which hydrolysis and microbial death are described by first-order kinetics, while the remaining stages are described by second order kinetics and the Monod equation is used to interpret the consumption of soluble compounds and the production of gas, in addition, it is assumed that under anaerobic conditions carbohydrates are hydrolyzed faster than proteins and lipids [25]. Table 2 shows the most critical reactions in these last three stages of anaerobic digestion, as well as an approximation of their kinetic constant.

Raw materials

In recent years, anaerobic digestion of wastes and residues from agriculture and industry, municipal organic waste, sewage sludge, etc. has become one of the most attractive renewable energy sources for industry, as it allows the reuse of raw materials, minimizes global warming and generates new sources of employment [26].

Indeed, a great variety of products and by-products could be used as raw material in anaerobic digestion processes as the animal manures. Different types of species can provide this, and its generation is assured. Table 3 shows the different manure-producing species.

As seen in Table 3, the species with the highest annual contribution of manure are cattle and horses, which ensures the use of this raw material.

Tabla 3. Producción de estiércol por especie.
Table 3: Manure production by species [27].

Species	Live weight (kg)	Production (kg/day)	Production (kg/year)
Swine	50	6	2190
Cattle	500	34	12410
Equines	500	10	3650
Sheep	15	1,5	548
Poultry	1,5	0,1	36,5

In biogas production, the manures most used as raw materials are those of pigs and cattle, which have a rich composition in organic matter. Tables 4 and 5 shows the composition of swine and cattle manure.

Tabla 4. Composición típica de sustrato porcino.
Table 4: Typical composition of swine substrate dry basis [20].

Sample	Carbohydrates (%)	Proteins (%)	Fats (%)	Ashes (%)
1	44,06	23	4,9	28,04
2	67,39	15,87	4,69	12,05
3	53,88	10,95	11,5	23,67

From Table 4, it can be concluded that the composition of a sample of porcine substrate represents 44.06% carbohydrates, 23% proteins, and 4.9% fats for a total of 72% volatile solids, but these can vary according to the sample.

Table 5 shows that the cattle substrate contains 53.13% volatile solids, demonstrating that swine manure contains a higher number of volatile solids due to its high carbohydrate and protein content, increasing biogas production from this source [28].

Tabla 5. Composición típica de sustrato vacuno.
Table 5: Typical composition of the bovine substrate [29], [28].

Characteristics	Composition (%)
Dry Matter	18,71
Organic dry matter	15,84
Crude protein	5,56
Carbohydrates	2,34
Lipids	0,87
Lignin	3,55
Cellulose	5,8
Free cations	0,46

In a more specific analysis, other characteristics of swine manure were found, which can be seen in Table 6.

Tabla 6. Características del estiércol de cerdo.
Table 6: Pig manure characteristics [1], [30].

Parameters	Value	Units
pH	7,8	-
Total solids	73,4 ± 0,4	Kg/m^3
Volatile solids	53,4 ± 0,4	Kg/m^3
COD (total)	95,2	$Kg\ O_2/m^3$
COD (soluble)	34,81 ± 0,7	$Kg\ O_2/m^3$
Total Kjeldahl nitrogen TKN	5,67 ± 0,1	g N/Kg
Inorganic nitrogen NI	0,275	$Kmol\ N/m^3$
Inorganic carbon CI	0,429	$Kmol\ C/m^3$

COD = Chemical Oxygen Demand

Taking into account what is reported in table 6, it can be seen that the total solids content is high with a value of 73.4%. This value influences the percentage of nitrogen and phosphorus during the process, favoring the development of bacterial families. The mobility of methanogenic bacteria within the substrate is increasingly limited as the solids content increases and therefore efficiency and gas production may be affected [29].

This raw material in biodigesters must be previously mixed with a quantity of water, which should not be stipulated a priori. It must be related to the amount of manure used, so Table 7 shows the relationship between the amount of manure and water.

Tabla 7. Relación estiércol-agua.
Table 7. Manure-water ratio [31].

Type of animal	Manure: Water
Bovine	1:2
Swine	1:3
Poultry	1:3

The manure-water ratio depends on the percentage of total solids contained in the manure and the percentage that is fed to the reactor. Therefore, bovine manure will need less water than swine manure or poultry manure, because the manure-water ratio that must be had between them is 1:2 for bovine and 1:3 for swine or poultry (see table 7). On the other hand, the total solids feed to the reactor must be between 8-12% [32].

pH implications

pH is one of the most critical variables in biogas production because a neutral pH is favorable for biogas production since most methanogens grow in the pH range of 6.7 to 7.5 [33], [34], [35]. Sometimes the decrease or increase in pH can lead to a decrease in the amount of biogas produced at the end of the process. Usually, the increase in pH is due to an increase in ammonia concentration, and the decrease in pH is due to an increase in volatile fatty acid concentration [36]. It is considered that the increase in the ammonia concentration is associated with an excess of nitrogen, which increases the speed of the process and brings about the inhibition of fermentation; since it destroys microorganisms. On the other hand, the increase in volatile fatty acids is closely linked to an excess of hydrogen, which inhibits or stops the process. However, thanks to the alkalinity of animal manure, a decrease in pH is prevented [29].When the pH value is low, ash, fertilizer, calcium hydroxide, or a mixture of both, diluted ammonia water and fermented liquor can be added [36]. If it is high, consider adding sulfur powder (150 to 250 g/m^3), iron sulfate (1 to 3 g/m^3), or acetylsalicylic acid (1 to 3 g/m^3) [37].

Temperature Implications

It is the most influential factor in the performance of biogas production since it directly affects the development of bacterial flora. For this reason, the increase in temperature produces a geometric increase in the rate of degradation and biogas production [38]. Temperature influences solubility, gas absorption, and viscosity. High temperatures increase the solubility of solids in the liquid phase and decrease the absorption of gases. Increased solubility accelerates the degradation process, and decreased absorption of gases such as H_2 or H_2S facilitates the fermentation process [31].

Thermophilic digestion has some advantages over mesophilic digestion:

- ✓ It can support higher organic loads due to faster reaction rates [38].
- ✓ High pathogen inactivation efficiency [6].
- ✓ Reduced HRT of the reactor, which usually lasts 15 days under thermophilic conditions and 20 to 25 days under mesophilic conditions [39].

- ✓ It may achieve better degradation of long-chain fatty acids (LCFA) [31].
- ✓ Produces a lower and more qualitative amount of digested effluent depending on the chemical composition of the substrates used [39].

There are also some disadvantages of thermophilic treatment, for example:

- ✓ The process requires more energy to maintain temperature [6].
- ✓ The feed biomass must enter at a high temperature [6].
- ✓ Temperature fluctuation is problematic for biogas production[6].

In the mesophilic range (25-45 °C) the temperature is similar to natural digestion, for this reason it presents a performance similar to this. It is necessary a retention time of approximately 20 days and a control of the agitation of the substrates [33], [39].

In the thermophilic range (45-65 °C) it has a shorter retention time, approximately 10 days, and greater control over the agitation of the substrates [31], [34], [35].

Carbon/Nitrogen Ratio

A balanced ratio between carbon sources and other nutrients such as nitrogen, phosphorus, and sulfur is most important for substrate composition. Both carbon and nitrogen are elements consumed by microorganisms for their development, so a higher C/N ratio could decrease the reaction rate and consequently increase the HRT, as well as reduce the amount of biogas generated, while lower values can cause ammonium inhibition [33], [35]. Table 8 shows the C/N ratios of the most commonly used raw materials in the biogas production.

Tabla 8. Relación carbono/nitrógeno de diferentes tipos de estiércoles.
Table 8: Carbon/nitrogen ratio of different types of manures[35].

Raw material	Carbone (%)	Nitrogen (%)	C/N Ratio
Dry rice straw	42	0,64	67:1
Dry wheat straw	46	0,53	87:1
Poultry manure	41	1,30	32:1
Sheep manure	16	0,55	29:1
Cow dung	7,3	0,29	25:1
Horse manure	10	0,42	24:1
Pig manure	7,8	0,60	13:1
Human excreta	2,5	0,85	3:1

Inhibitors

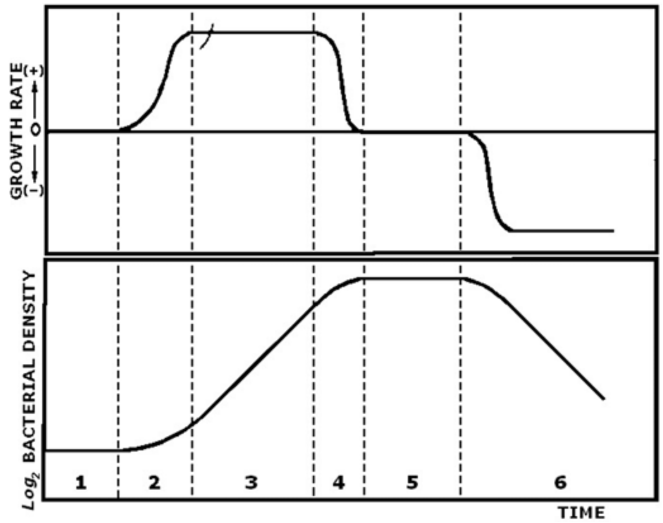
Inhibition is understood as the reduction of the maximum rate of bacterial growth; inhibitors are compounds that slow down the development of bacteria and even stop it [40]. Table 9 shows some of the main substances that affect or inhibit the biogas production process inside the digester.

Tabla 9. Concentración de inhibidores communes.
Table 9: Common inhibitor concentration [29].

Inhibitors	Inhibitory concentration	Inhibitors	Inhibitory concentration
SO_4	5000 ppm	CN	25 mg/L
NaCl	40000 ppm	Synthetic detergent	20-40 mg/L
Nitrate	0,05 mg/Ml	Na	3500-5500 mg/L
Cu	100 mg/L	K	2500-4500 mg/L
Cr	200 mg/L	Ca	2500-4500 mg/L

As can be seen, small amounts of compounds in low concentrations, such as nitrate, can decrease biogas production in the reactor.

Figura 2. Fases del desarrollo bacteriano y su relacion con la produccion de biogas.
Figure 2. Phases of bacterial development and their relationship with the production of biogas [29].



Biogas production yield is closely related to bacterial growth, but determining the correct organic loading rate allows you to optimize reactor performance and maximize methane production. This yield is measured by the amount of gas that can be produced per unit volume of volatile solids contained in the feedstock after exposing in to anaerobic digestion for a sufficient time at a given temperature and specified conditions [41].

In figure 2, it can be seen that there is an initial period where the growth rate is zero (lag phase), followed by an increase in speed (acceleration phase). Subsequently, a constant growth rate (exponential phase) and a decrease in rate (lag phase) follow. The velocity decreases until it is zero (stationary phase) and continues until it becomes negative (decaying phase). So biogas production is very closely related to bacterial growth [29].

Raw Material Yields

Following are the methane production yields, taking into account the percentage of dry matter and volatile solids, based on the review of scientific literature.

Tabla 10. Rendimiento de biometano a partir de materias primas seleccionadas.
Table 10: Biomethane yield from selected feedstocks [26].

Feedstocks	DM (%)	VS (%)	Yield (CH_4/kg SV)	Yield (CH_4/kg fresh)
Pig slurry	3-8	70-80	250-350	6-22
Poultry slurry	10-30	70-80	300-350	21-84
Maize sillage	30-40	90-95	250-450	68-170
Grass	20-30	90-95	300-450	55-128
Potatoes	20-30	90-95	280-400	54-128
Straw	85-90	80-90	200-250	136-202
Vegetable waste	85-90	80-90	200-251	136-203
Organic waste	10-40	75-90	350-450	26-180
Slaughterhouse waste	35	90-95	550-650	173-216

DM = Dry matter; VS = Volatile solids (% DM)

Table 10 shows that the highest methane yield in volatile solids is obtained using slaughterhouse waste and organic waste, while manures present the lowest yields and this is due to the high content of hemicellulose and lignin present in the cell wall, hindering the degradation of the biomass and opposing the enzymatic activity, which leads to an inhibition of the process [42].

Currently, in some countries, crops are grown to generate raw materials for biogas production. Therefore, analyzing the methane yield per hectare of these intensive crops is important.

Tabla 11. Rendimiento de cultivo y rendimiento de metano obtenido mediante digestión anaeróbica.
Table 11. Crop yield and methane yield obtained by anaerobic digestion [43].

Crop	Crop yield (ton crop/ha)	Methane yield (m^3/kg ODS)
Sugar beet	40-70	0,39-0,41
Foreign beets	80-120	0,40-0,42
Maize	40-60	0,29-0,34
Corn cob	10-15	0,35-0,36
Wheat	30-50	0,35-0,38
Sorghum	40-80	0,29-0,32
Grass	22-31	0,29-0,32
Red clover	17-25	0,30-0,35
Wheat grain	6-10	0,37-0,40
Rye grain	4-7	0,30-0,41

Table 11 shows that the highest yields are found in sugar beet crops and as a foreign beets, representing a higher crop yield per hectare, although the most commonly grown crops are corn, sunflower, and grass [43].

The methane yield of some fruit and vegetable wastes, which can be used in biofuel production, was also analyzed.

Tabla 12. Rendimiento de metano obtenido mediante digestión anaerobia de residuos de frutas y hortalizas.
Table 12. Methane yield obtained by anaerobic digestion of fruit and vegetable wastes [43].

Type of waste	Methane yield (m^3/kg ODS)
Mango peels	0,37-0,52
Banana peels	0,24-0,32
Orange pressings	0,50
Mandarin peels	0,49
Whole (rotten) mandarins	0,50
Pressed lemons	0,47
Tomatoes (rotten)	0,21-0,38
Onion outer skins	0,40

Table 12 shows that of the fruit and vegetable wastes, the ones with the highest yields are orange pressings and whole rotten mandarins.

On the other hand, fruit and vegetable wastes degrade very easily, and it is recommended to co-digest them with other raw materials since hydraulic retention times are greater than 60 days and their availability is for food use, so mixing them with other raw materials guarantees higher percentages of methane production in less time [43].

Although a series of raw materials have been presented with appreciable values of methane production yields according to their composition of dry matter and volatile solids, it can be seen that among the different studies analyzed, these present percentages of differences in the total performance of biogas obtained. An important point is the variety of raw materials that are becoming increasingly important for this process to be used as feed.

Table 13 present the research results related to the methane yield obtained according to the selected feedstock.

Tabla 13. Producción de biogás a partir de sustratos seleccionados.
Table 13: Biogas production from selected substrates [6], [44], [45].

Substrate	Dry matter (DM) (%)	Performance of biogas (m^3/kg DM)	Methane concentration (%)	Methane yield (m^3/kg VS)
Pig manure	8-17	3,6-4,8	70-80	0,25-0,35
Cow manure	8-16	0,2-0,3	55-75	0,20-0,25
Chicken manure	25	0,35-0,8	60-80	0,30-0,35
Sewage sludge	20	0,35-0,50	65-70	0,30-0,40
Corn	20-48	0,25-0,40	52	0,25-0,45
Sugar beet	19-22	0,39-0,76	53	0,23-0,38
Wheat	88,9	0,65-0,7	54	-

In the previous table, it can be noticed that the highest performance of biogas is generated by pig manure with a methane concentration between 70% and 80%.

Tables 14 and 15 present a more detailed study since they take into account the type of reactor to be used, the volume of raw material, the hydraulic retention time (HRT), the temperature at which each experiment is carried out, the organic load rate (OLR) supplied to the digester, the type of substrate that can be considered, as well as the biogas production rates generated, and the percentage of methane obtained.

Tabla 14. Desempeño de digestores anaeróbicos domésticos en América Latina: resultado de investigación a escala de laboratorio.
Table 14: Performance of domestic anaerobic digesters in Latin America: results of laboratory-scale research [33].

Designs	T	V	HRT	Substrate	OLR	Biogas production rate	Specific biogas production	CH_4
Reactor	°C	m^3	Days		$kg\ VSm_{dig}^{-3}d^{-1}$	$m_{biogás}^{3}m_{dig}^{-3}d^{-1}$	$m_{biogás}^{3}kg_{VS}^{-3}$	%
CSTR	11 35 35	0,0002	50	Cow dung Llama manure	0,52-3,22 0,89-4,43	0,03-0.07 0,10-0,31 0,12-0,34	0,01-0,06 0,10-0,19 0,06-0,18	39-56 46-61 42-57
CSTR	25 32	0,0009	30	Llama, cow, and sheep dung (33.33 of each in VS)	2	0,24 0,31	0,12 0,16	56 56
CSTR	25	0,0002	30	Co-digestion of llama, cow and sheep manure, quinoa, cattail, and aquatic flora (different proportions of 8 to 58% of each in SV).	1,8	0,33-0,70	0,18-0,39	46-54
CSTR	35	0,0002	10-70 30	Co-digestion of manure (cow manure 71% by weight and swine manure 29% by weight). Manure (cow manure 71% by weight and swine manure 29% by weight) Co-digestion of manure (cow manure 71% by weight and pig manure 29% by weight), fruit and vegetable waste, and slaughterhouse waste from cattle and pigs.	0,14-3,80 1,31	0,03-1,01 0,45 0,22-0,89	0,24-0,62 0,34 0,17-0,68	44-59 56 25-57
CSTR	18 25 25	0,0002	30 50	Co-digestion of llama, sheep, and cow manure (33.3% of each in VS). Co-digestion of llama, sheep, and cow manure (different proportions of 16.5 to 67% of each in SV)	0.50-8,10 1,2	0,03-0,23 0,07-0,48 0,16-0,32	0,02-0,09 0,04-0,15 0,14-0,26	42-58 39-54 46-54

HTR = hydraulic retention time; OLR = Organic loading rate

Table 14 shows that only the use of the CSTR type reactor is proposed, with temperatures ranging from 11 °C to 35 °C, small volumes, and hydraulic retention time of up to 70 days. The interesting aspect of this study is the use of llama manure as a raw material since it has not been mentioned in other studies. It can be seen that the highest biogas production is generated when a mixture of bovine (71%) and pig (29%) manure is used, but it should also be noted that the raw material that generates the highest methane content is cow manure with a percentage of 61%. On the other hand, in the codigestion of cow, sheep and llama manure, a higher yield was expected compared to the same non-codigested manures, but this is due to a higher ammonium content in the llama manure, affecting methane production [33].

Table 15 shows the analysis results when a tubular reactor is implemented, adjusted to temperature range, volume, and hydraulic retention time. Also, it has the particularity of using guinea pig manure as substrate and technology according to the geographical region, divided between coastal cities (Colombia, Cuba and Costa Rica) and high latitudes (Peru and Bolivia).

The highest specific biogas production was obtained from cow and sheep manure and the lowest biogas production from guinea pig manure, this es due to low digestibility and net energy content, which is greatly influenced by the species, age and type of feeding [30], [33].

The highest percentage of methane was obtained from pig manure, while the lowest was obtained when pig manure was mixed with water in batch reactors. This may be related to the manure-water ratio or to the source from which the water was obtained, since if it contains any type of inhibitor (see table 9), methane production is compromised [33].

Tabla 15. Desempeño de digestores domésticos a pequeña escala en América Latina: resultado de una investigación piloto y a gran escala.
Table 15: Performance of household and small-scale digesters in Latin America: results of a pilot and large-scale investigation [46], [22], [47], [48], [49].

Designs	T	V	HRT	Substrate	OLR	Biogas production rate	Specific biogas production	Methane
Reactor	°C	m^3	Days		$kg\ VSm_{dig}^{-3}d^{-1}$	$m_{biogás}^3 m_{dig}^{-3} d^{-1}$	$m_{biogás}^3 kg_{VS}^{-3}$	%
Coastal and tropical regions (Colombia, Cuba y Costa Rica)								
Polyethylene tubular	24-25	12,3	16	Pig manure	1,17	0,28 (x) 0,25 (y)	0,24 (x) 0,21 (y)	-
Polyethylene tubular	25-27	68 49	39 14	Cow manure Swine manure	1,01 1,28	0,40 (x) 0,39 (y) 0,12 (x, y)	0,40 (x) 0,38 (y) 0,10 (x, y)	62,60 76,40
Polyethylene tubular	22-26	0,2	40	Co-digestion of pig manure and used cooker - lubricating grease (2.5 % by volume)	0,73	0,34 (x) 0,31 (y)	0,46 (x) 0,42 (y)	66,90
High altitude (Perú y Bolivia)								
PVC Tubular	22-23	7,5	75	Guinea pig manure	0,60	0,04 (y, z)	0,06 (y, z)	65
PVC Tubular	16-20	7,5 7,5	60 60	Guinea pig manure Co-digestion of Cow (92.5% by weight) and guinea pig manure (7.5% by weight)	1,01 0,82	0,03 (y, z) 0,08 (z) 0,07 (y)	0,03 (y, z) 0,10 (z) 0,08 (y)	60 55
Polyethylene tubular	13-19	0,88 0,84 0,86	80	Cow dung Llama manure Co-digestion of sheep and llama manure	0,44	0,09-0,12 (x) 0,07 (y) 0,11-0,14 (x) 0,10 (y) 0,06 (x) 0,05 (y)	0,20-0,27 (x) 0,17 (y) 0,25-0,32 (x) 0,22 (y) 0,15 (x) 0,11 (y)	47,80 46,70 45,60
Biogas volumes expressed: (x) at local conditions; (y) at 0 °C and 1 atm; (z) at 20 °C and 1 atm..								

Co-digestion

Co-digestion is the process in which different types of raw materials are mixed to optimize the decomposition of the material fed to the digester and to obtain the most significant amount of biogas possible. It has been demonstrated that this strategy can associate different types of feedstock with taking advantage of them and increasing the degradation of organic matter inside the reactor, as shown in Tables 14 and 15.

Solids concentration

The total solids concentration in the digester should vary between 7% and 10%. Particle size is not essential compared to other parameters such as pH and temperature. However, the particle size affects degradation and, ultimately the biogas production [33], [35].

An initial variation between dry and wet fermentation can be defined. The term « dry fermentation » describes the degradation process, which is characterized by a high solids content ranging from 15% to 35% (or even higher for batch-type reactors using solid waste), while, on the contrary, during « wet fermentation », the solids content is up to 10% and therefore the liquid content is comparatively higher [50].

Experimental Data

The previous sessions established the essential data of the scientific literature. In this section, the data obtained in the start-up phase of the biodigester located in the organic materials transformation laboratory of the Universidad del Atlántico will be analyzed (see figure 1).

Table 16 shows the characteristics and working conditions of the biodigester in the start-up stage located in the facilities of the Universidad del Atlántico.

Tabla 16. Características de la materia prima y condiciones de operación experimentales.
Table 16. Raw material characteristics and experimental operating conditions

Characteristics	Content
Total solids	12%
Reactor volume	1000 L
Agitation	40 rpm
HRT	25 days
C/N ratio	13,42:1
pH	6,8 and 7,5
Solids suspended totals	18250 mg/L
Solids suspended volatiles	22250 mg/L
Organic load	40 L/day
Volatile fatty acids (VFA)	From 8000 and 20000 mg/L
Alkalinity	From 3000 and 12000 mg/L
Inoculum	A solution of 5% solids was taken total distilled water and rumen, stabilized pH to the inoculum with NaOH and sealed in a 1.5 L reactor leaving a space for the 30% gas, then purge was performed with nitrogen to ensure an environment without oxygen, was left in production in a bath thermostat at 40 °C until obtaining a percentage of methane above 60% Vol. (15 days) and this was later used as inoculum in a larger reactor.

As can be seen in the previous table, the conditions under which the start-up stage was carried out are within the parameters found in the review of the scientific literature, such as the values related to the total solids, the hydraulic retention time, the C/N ratio and volatile and total suspended solids, among other factors.

The data obtained in the execution phase of this biodigester are tabulated in Table 17, which were collected in approximately 32 days in a batch reactor.

Table 17 summarizes the data of the from the startup stage in the laboratory, showing that initially the reactor was loaded with a biomass (rumen) volume of 130.87 liters, to which volumes of 30 to 40 liters/day of substrate were added (in undefined periods, since they could allow 1 to 3 days to pass before reloading), until reaching a volume of 667.87 liters, which represents 70% of the total level of the reactor. This biomass percentage is the maximum that can be loaded into the reactor; Since, as previously established, the other 30% is for the biogas produced or the foam that can be generated throughout the process.

It can also be seen that the COD was monitored during the period that the experiment lasted. Although it was not measured every day, the values taken fluctuated throughout these 32 days but remained around 52109 mg/L, which is very similar to that reported in Table 6 for this type of substrate (34.81 ± 0.7 kg O_2/m^3).

For the values of volatile organic acids (FOS) and total inorganic carbonate (TAC), it can be seen that although the FOS and TAC vary throughout the period and that they were not measured every day, they remain around the 12364 and 7687 mg/L, respectively. It can be noted that the average TAC (alkalinity) value is related to that reported in Table 6 (CI 0.429 kmol C/m^3), which is approximately equal to 5148 mg/L, for the case of FOS, no value related to this measurement was found.

As for pH, an average value of 6.8 was obtained. This value differs from that reported in Table 6 for this substrate (7.8). This difference could be associated with the characteristics of the raw material and the conditions of the medium.

In this startup period in also shows the production of methane, carbon dioxide, hydrogen sulfide, ammonia, oxygen, and others compound throughout the days. The results show that in the first days, there is no biogas production. This is due to the organic decomposition stage. However, their concentration increases as the biodigester is loaded.

Tabla 17. Datos obtenidos en una de las corridas en el reactor por lotes en los laboratorios de la UA.
Table 17: Data obtained in one of the batch reactors runs at the AU laboratories.

Day	Load (L/day)	Volume (L)	Level reactor (%)	COD (mg/L)	FOS (mg/L)	TAC (mg/L)	FOS/ TAC	pH	CH_4 (%)	CO_2 (%)	H_2S (%)	NH_3 (%)	O_2 (%)	Others (%)
0	130,87	130,87	3	-	-	-	-	-	0	0	0	0	0	0
1	0	130,87	3	52050	-	-	-	6,88	0	0	0	0	0	0
2	0	130,87	3	-	-	-	-	6,88	0	0	0	0	0	0
3	0	130,87	3	-	-	-	-	6,88	0	0	0	0	0	0
4	0	130,87	3	71775	17431	8753	1,992	6,94	0	0	0	0	0	0
5	0	130,87	3	-	-	-	-	6,94	0	0	0	0	0	0
6	40	170,87	9	50050	18882	10338	1,820	6,56	0	0	0	0	0	0
7	40	210,87	14	-	-	-	-	6,59	0	0	0	0	0	0
8	0	210,87	14	-	-	-	-	6,59	0	0	0	0	0	0
9	0	210,87	14	-	-	-	-	6,39	0	0	0	0	0	0
10	30	240,87	17	-	-	-	-	6,39	8	13,4	0,1176	0,0475	0,10	78,33
11	0	240,87	17	51825	17333	8468	2,470	6,40	8	13,4	0,1176	0,0475	0,10	78,33
12	40	280,87	22	-	-	-	-	6,34	8	13,4	0,1176	0,0475	0,10	78,33
13	0	280,87	22	-	-	-	-	6,27	8	13,4	0,1176	0,0475	0,10	78,33
14	40	320,87	27	-	-	-	-	6,41	12,9	17,5	0,0936	0,0393	0,10	69,37
15	0	320,87	27	-	-	-	-	7,10	12,9	17,5	0,0936	0,0393	0,10	69,37
16	0	320,87	27	-	-	-	-	7,10	12,9	17,5	0,0936	0,0393	0,10	69,37
17	40	360,87	32	-	-	-	-	6,88	23	26,9	0,0652	0,0273	0,10	49,91
18	40	400,87	37	53267	9558	3881	2,463	6,90	27,1	30,5	0,0953	0,0396	0,10	42,17
19	28	428,87	41	-	-	-	-	6,89	30,8	31,5	0,0979	0,0413	0,10	37,46
20	42	470,87	46	-	-	-	-	6,84	36,1	31,7	0,0946	0,0395	0,10	31,97
21	0	470,87	46	-	-	-	-	6,90	40,5	31,4	0,0780	0,0328	0,10	27,89
22	0	470,87	46	-	-	-	-	6,90	40,5	31,4	0,0780	0,0328	0,10	27,89
23	37	507,87	51	-	-	-	-	6,90	40,5	31,4	0,0780	0,0328	0,10	27,89
24	40	547,87	56	42800	10212	6676	1,530	6,94	62,4	34,3	0,0683	0,0275	0,10	3,100
25	40	587,87	61	-	11631	7285	1,597	6,84	66,5	31,2	0,0349	0,0139	0,10	2,150
26	0	587,87	61	43000	8870	4957	1,789	6,90	70,3	28,5	0,0258	0,0108	0,10	1,060
27	40	627,87	66	-	-	-	-	6,84	72,4	27,5	0,0221	0,0087	0,06	0,009
28	0	627,87	66	-	-	-	-	6,84	72,4	27,5	0,0221	0,0087	0,06	0,009
29	0	627,87	66	-	-	-	-	6,84	72,4	27,5	0,0221	0,0087	0,06	0,009

30	0	627,87	66	-	-	-	-	6,84	72,4	27,5	0,0221	0,0087	0,06	0,009
31	40	667,87	70	-	8679	11574	0,767	6,85	72,1	27,2	0,0255	0,0085	0,06	0,006
32	0	667,87	70	-	-	-	-	6,81	72,4	27,6	0,0320	0,0119	0,04	0,006

FOS = volatile organic acids; TAC = total inorganic carbonate

In general, it can be said that the values reported in the scientific literature are related to those found in the start-up phase of the biodigester in the laboratory of transformation of organic materials and are undoubtedly a guide to how the system is behaving and the variabilities that can be generated in it. Now, both data matrices are important in the development of this technology, since they can be used considering the different related raw materials.

4. CONCLUSIONS

Two main chemical equations were identified; stoichiometric equations in the hydrolysis stage and kinetic in the acidogenic, acetogenic and methanogenic stages, where the former takes the conversion fraction into account and the latter the kinetic constants.

Temperature is one of the most influential factors in the performance of biogas production, since it directly affects the development of the bacterial flora. For this reason, the increase in temperature produces a geometric increase in the speed of biogas degradation and production, temperature influences solubility, gas absorption and viscosity.

A decrease or increase in pH can lead to a decrease in the amount of biogas produced at the end of the process. Normally the increase in pH is due to the increase in the concentration of ammonia and its decrease to the increase in the concentration of volatile fatty acids.

Manure has been identified as the best co-digestion material to combine with high-fat waste due to its high alkalinity.

A high carbon/nitrogen ratio could decrease the reaction rate and consequently increase the TRH, as well as reduce the amount of biogas generated, while lower values can cause ammonia inhibition.

Different feedstocks, such as manures, agricultural residues, fats, crops, sludge, and food waste, can be used for biogas generation in domestic and industrial digesters. Which indicates the continuous energy generation and guarantees the application of anaerobic digestion.

Co-digestion allows the utilization of several substrates simultaneously, which allows increasing the degradation of organic matter inside the reactor and, consequently, the quality of the biogas. This is possible thanks to the fact that it increases the load of easily biodegradable matter depending on the chemical composition of the substrates used, it improves the buffering capacity of the influent mixture keeping the pH levels within the range for methanogenesis, it provides a better balance of nutrients, especially to improve the C/N ratio, it dilutes the inhibitory compounds avoiding the deterioration of the anaerobic digestion process, it leads to a greater volumetric production of methane, it promotes synergistic effects that lead to an advanced biodegradation and it contributes to the solution of problems related to the agitation or pumping of digesters, especially in the processing of solid waste.

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