Enhancing Anaerobic Digestion Process: A Comprehensive Optimization Study

Camila Santos Oliveira[1*], Luciano Sergio Hocevar[1], Jadiel dos Santos Pereira[1], Felipe Andrade Torres[1], Carine Tondo Alves[1]

[1]Federal University of Recôncavo da Bahia; Feira de Santana, Bahia, Brazil

Anaerobic digestion constitutes a series of chemical reactions facilitated by anaerobic microorganisms, wherein organic matter is converted into biofuels. We did a bibliometric study to comprehend the factors influencing the optimization of this process. This investigation underscored crucial parameters affecting methane and biogas production: temperature, pH, hydraulic retention time (HRT), carbon-to-nitrogen ratio, and sample preparation and treatment procedures. We recommend an average of parameters as T = 35°C, pH = 6, HRT = 21 days, and total chemical oxygen demand > 8.5 COD/m³.d to attain optimal outcomes, it is recommended to maintain. By adhering to these guidelines, the process can be enhanced, thereby fostering greater efficiency in biogas production.

Keywords: Anaerobic Digestion. Biogas. Biomethanogenesis.

Anaerobic digestion is a metabolic process that decomposes organic matter in an oxygen-free environment. It involves a series of chemical reactions (Figure 1) facilitated by anaerobic microorganisms, which thrive in environments devoid of oxygen [1]. This natural process occurs in specific soils and sediment at the bottom of water bodies where oxygen cannot penetrate. Additionally, it finds practical applications in various industries, such as producing dairy products, beer, ethanol, and silage. Anaerobic digestion also plays a pivotal role in sewage treatment plants (ETEs) and serves as a renewable energy source by generating biogas. The process can be divided into four phases: hydrolysis, acidogenesis, acetogenesis, and methanogenesis [1].

Hydrolysis constitutes a fundamental step in anaerobic digestion, wherein high molecular mass compounds such as lipids, polysaccharides, and proteins are broken down into more straightforward and soluble organic substances (monomers). This pivotal process is facilitated by hydrolytic bacteria that secrete extracellular enzymes [1,2]. When addressing complex and recalcitrant organic matter, hydrolysis is critical in the overall degradation rate and may be considered a limiting factor [3].

Transitioning to Acidogenesis, the monomers produced during hydrolysis serves as a substrate for diverse anaerobic and facultative bacteria, culminating in forming short-chain organic acids. For example, carbohydrates like glucose undergo degradation into pyruvate, subsequently transformed into lactic acid by Lactobacillales and further metabolized into ethanol through yeast action. This intricate series of reactions yields acetate, ammonia, carbon dioxide, and hydrogen sulfide as products [4].

The third stage, executed by a group of bacteria known as acetogens, assumes critical significance in anaerobic digestion. In this phase, long-chain acids are converted into one or two-carbon atom acids, namely formic and acetic acids, concurrently generating hydrogen and carbon dioxide as byproducts. The reaction equilibrium's direction, involving hydrogen and carbon dioxide consumption for acetate production, is regulated by homoacetogenic bacteria [5].

Lastly, methanogenesis represents the ultimate phase and occurs exclusively under anaerobic conditions. During this stage, carbon within the biomass is transformed into carbon dioxide and methane through the enzymatic activity of

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Address for correspondence: Camila Santos Oliveira. Av. Centenário, 697 - Sim. Zipcode: 44085-132. Feira de Santana, Bahia, Brazil. E-mail: camilaoliveira@aluno.ufrb.edu.br.

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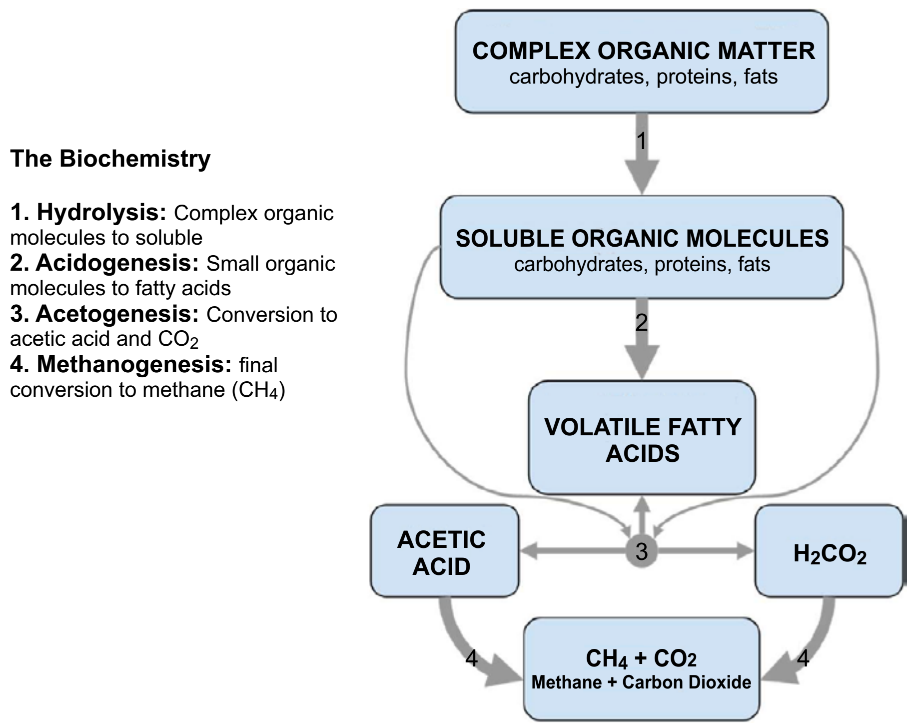
Figure 1. Anaerobic digestion scheme.



methanogenic archaea [6]. Optimizing parameters within the anaerobic digestion process is paramount for maximizing biogas production efficiency. Several vital factors significantly influence the system's performance, including feedstock selection, operating temperature, hydraulic retention time (HRT), pH level, and organic loading rate (OLR). Properly managing and controlling these parameters create favorable conditions for the diverse microbial community responsible for anaerobic degradation. Optimal conditions facilitate the breakdown of complex organic matter into valuable biogas, predominantly methane, thereby enhancing production.

Moreover, fine-tuning these parameters increases biogas yield mitigates process instability and prevents potential inhibition or failure. Effective management and optimization of these factors are crucial for sustainable biogas production, offering a renewable energy source while promoting waste valorization and environmental benefits.

A rigorous exploratory research was conducted to comprehensively understand these influential factors, employing a bibliometric review on the Google Scholar platform. This systematic investigation utilized carefully selected keywords, specifically "anaerobic digestion AND optimization." The study analyzed a wide range of scholarly articles, publications, and academic resources by employing bibliometric techniques.

This approach synthesized and analyzed relevant and up-to-date information regarding anaerobic digestion process optimization, revealing crucial insights and trends in the field. Using Google Scholar, a reputable academic search engine, ensures access to a diverse array of scholarly works, contributing to the robustness and validity of the research findings.

Materials and Methods

A bibliometric search was conducted on Google Scholar using the search terms "anaerobic digestion AND optimization." The search encompassed a broad timeframe without specific publication date restrictions, facilitating a comparison between newer and older information. The results returned 11,100 articles in Portuguese and 235,000 articles in English. Among these, the top 10 articles from each search, ranked by relevance, were selected for further analysis. Remarkably, all the top 10 articles from the Portuguese search were authored in Brazil. In comparison, 50% of the top 10 articles from the English search originated from Asia, with the remainder originating from North America and Europe. In this review, article selection criteria were based on relevance, as determined by the platform and their alignment with the proposed research theme.

The abstracts of the top 10 articles from each search were meticulously examined, and those deemed most pertinent to the research were included in this review, while others were excluded. The excluded articles focused on related subjects, particularly optimizing anaerobic digestion using algorithms.

Results and Discussion

A series of biodigestion experiments should be conducted, where all other variables are kept constant while selectively altering the parameter under scrutiny. This approach allows for the comprehensive assessment of the variables that significantly influence optimal reactor production

The bibliometric review encompassed publications presenting outcomes of studies within this genre, elucidating various investigations in this area. Throughout biodigestion experiments, crucial data are collected and analyzed to comprehend how specific factors influence reactor performance.

These factors may include temperature, pH levels, organic loading rate (OLR), hydraulic retention time (HRT), and the type of feedstock used. Researchers can derive valuable insights into their effects on biogas production efficiency and the overall process by systematically changing and observing these variables.

Through this bibliometric review, a significant volume of pertinent literature was surveyed, presenting diverse findings from various studies focused on optimizing reactor performance. Examining these publications enables researchers and practitioners to comprehensively understand the key factors influencing biodigestion and identify successful strategies for enhancing biogas yields and process stability (Table 1). With access to the data and outcomes of these biodigestion experiments through the reviewed publications, future researchers and industry professionals can leverage a wealth of knowledge to effectively optimize their reactor systems and contribute to the sustainable utilization of anaerobic digestion for biogas production.

Leite and colleagues [7] conducted a study to ascertain the most influential parameters for anaerobic co-digestion of cassava wastewater and coffee husks, utilizing bovine manure as an inoculum. Over 15 days, the researchers monitored biogas production from the mixture of inoculum and substrate, incorporating micronutrients into the process. Employing a Büchner flask as a reactor equipped with a gasometer coupled to a PVC hose, separate tests were conducted to evaluate the impact of various variables on reactor optimization.

The findings underscored the significance of both physical reaction conditions, such as acidity and temperature, and the concentrations of the inoculum and substrate, alongside nutrient addition. Through rigorous analysis, optimal values for the process were determined: 40 mL of cassava wastewater, 95 mL of coffee husks, and 40 mL of bovine manure. Maintaining a pH of 6 was identified as crucial, adding 1.5x106 UFC. mL^{-1} of bacterial inoculum and a temperature of 30°C Additionally, including 46.97 $mg.L^{-1}$ of $FeSO_4.7H_2O$ and 4.41 $mg.L^{-1}$ of $MnSO_4.H_2O$ proved beneficial for maximizing biogas production.

These results illuminate the intricate interplay of various variables in anaerobic co-digestion processes, emphasizing the importance of optimizing substrate and inoculum concentrations, physical reaction conditions, and nutrient supplementation. By identifying these optimal values, the study offers valuable insights for enhancing biogas production efficiency and guiding future research in biogas technology.

Reichert [8] conducted a comprehensive study investigating the correlation between various key variables in anaerobic digestion, focusing on waste composition, volatile solids, feed rate/organic load rate (TCO), pH, temperature, Carbon/Nitrogen ratio, mass residence time in the reactor, and reactor mixture. Reichert continuously analyzed several ETE reactors, utilizing sewage from different treatment plants as inoculum and organic material as substrate without additional additives. The study provided crucial insights into factors significantly influencing anaerobic digestion, identifying optimal points for these variables. TCOs above 8.5 COD/m^3.d were advantageous for enhanced biogas production, along with the use of organic wet residues with lower lignin and cellulose content, leading to a higher rate of biodegradable volatile solids.

The pH range of 5.5 to 8.5 and temperature between 30 °C and 35 °C were conducive to maximizing biogas production. A Total Hydraulic Retention (THR) of 14 days was ideal for digestion. Additionally, the study assessed the advantages and disadvantages of each reactor type used, providing valuable insights into suitable reactor configurations for specific applications.

Reichert's [8] study significantly advances our understanding of anaerobic digestion processes by elucidating critical variables and their optimal points. The findings offer practical guidelines for optimizing biogas production, which is essential for developing more efficient and sustainable waste treatment systems.

In another study by Deodato [9], WWTP sludge was used as inoculum and a hydrolyzate of the Organic Fraction of Urban Solid Waste along with pure glycerol and glycerol of industrial origin as substrate. Methanogenesis reactors were employed, and parameters including temperature, pH, and redox potential were measured over 6 months, with a Total Hydraulic Retention (THR) of 21 days. Co-digestion with pure glycerol showed potential for achieving an optimized carbon/nitrogen ratio, which is theoretically advantageous for maximizing biogas production. The study demonstrated promising results, with biodegradable volatile solids reaching approximately 6% m/v ST and about 4.5% m/v SV.

Deodato's [9] research contributes valuable insights into anaerobic digestion, particularly in co-digestion with glycerol-based substrates. The findings underscore the importance of exploring diverse substrates and inoculum combinations to enhance biogas production efficiency, promoting sustainable waste treatment solutions. These studies collectively play a pivotal role in advancing renewable energy production and waste management practices worldwide.

Several works have predominantly focused on algorithmic optimization and code construction. In cases where experimental data were provided, they often presented qualitative and quantitative information from reviews rather than experimental research. However, certain studies, such as the one conducted by Meegoda and colleagues [10], delved into essential variables such as chemical oxygen demand, carbon-nitrogen (C/N) ratio, theoretical methane yield, volatile solids, hydraulic retention time (HRT), total solids, temperature, and mass pre-treatment. Optimal points identified in their study included C/N ratios of 25:1 for mesophilic digesters and 35:1 for thermophilic digesters, HRT between 15-30 days, pH levels between 5-7, and temperatures ranging from 30-50 ºC. Similarly, Bandgar and colleagues [11] addressed the importance of temperature, C/N rate, organic load rate, HRT, pH, and alkalinity in controlling the anaerobic digestion process.

However, explicit parameters were not established in their review article. Conversely, Srivastava [12] considered a range of AD process optimization variables, including pH, temperature, supply rate, C/N rate, solids liquids rate, alkalinity, HRT, fixed and volatile solids, number of stages, sludge characteristics from sewage treatment plants (WWTP), and substrate pre-treatment, with an HRT of 40 days.

Table 1 compares the most cited parameters standard to many articles. A relatively large discrepancy can be observed in the recommended temperature ranges. This variation arises from the different experimental regimes used, i.e., mesophilic or thermophilic, which promote the proliferation of distinct bacterial communities at varying temperatures. Additionally, authors who mentioned the addition of a catalyst noted its beneficial effect on methane production. Deodato [9] worked with manure and others using sewage treatment plant waste in their studies.

Temperature exerts a significant influence on the anaerobic digestion process. Firstly, it directly correlates with the composition of the active microbial consortium, as each species thrives within a specific temperature range. Two main ranges are recognized: Mesophilic, spanning 20–45 °C, and Thermophilic, ranging from 45–0 °C, with optimal values cited as 35 °C and 55 °C, respectively. Elevated temperature accelerates reactions, consequently enhancing biogas production.

Furthermore, temperature impacts reactor acidity. Decreased temperature leads to higher volatile acid concentrations, potentially reducing the anaerobic process's buffering capacity and lowering pH. pH fluctuations significantly affect anaerobic digestion microorganisms, particularly methanogenic bacteria, are susceptible to extreme acidity. Thus, maintaining pH stability is imperative [7]. However, Deodato [7] notes that the pH range may be adjusted depending on the reaction phase, creating a favorable environment for specific microorganisms. For instance, maintaining a pH range of 5.5 to 6.5 during acidogenesis facilitates initial acid formation, while a range of 6.5 to 8.2 during acetogenesis and methanogenesis optimizes subsequent reaction phases. Hydraulic retention time (HRT) denotes the duration of liquid remains in the reactor, representing the time required for complete substrate digestion. It is computed as the ratio of digester volume to flow rate. Shorter HRTs are less efficient for lignocellulosic material digestion but are cost-effective [11].

Leite and colleagues [7] incorporated $FeSO_4.7H_2O$ and $MnSO_4.H_2O$ into their reactor as nutrients, providing sustenance for microbes. Adding nutrients can bolster microbial growth, enhancing anaerobic digestion by improving carbon and nutrient balance. There are optimal dosages for such additions, as excessive metals can become inhibitory or toxic. However, the study revealed that the highest CH_4 yields were achieved at high and low concentrations.

Deodato [9] utilized pure glycerol and glycerol of industrial origin. Glycerol inherently possesses high biodegradability and carbon content, achieves an optimized Carbon/Nitrogen

Table 1. Parameters that appeared most frequently and their values.

Authors	Temperature (°C)	Catalyst	pH	HRT	Reference
Leite and colleagues	30	$FeSO_4.7H_2O$ $MnSO_4.H_2O$	6	15	[7]
Reichert GA	30 – 35	-	5,5 – 8,5	14	[8]
Deodato AM	50 ± 1	Pure glycerol	6,5 – 8,2	21	[9]
Meegoda and collea-gues.	30 – 55	-	5 – 7	15 - 30	[10]
Bandgar and colleagues	35 – 55	Biochar	5,5 – 6,5	-	[11]
Srivastava SK	19.85	-	~8	30 – 40	[12]

ratio theoretically, facilitating enhanced biogas production.

Bandgar [11] employed Biochar, a form of biomass originating from plant material processed through pyrolysis. Biochar is rich in monovalent and divalent cations, accelerating carbonation reactions between CO_2 and water and forming carbonic acid. Its high porosity and extensive contact surface also enable it to serve as a CO_2-sequestering medium during anaerobic digestion.

Conclusion

The bibliometric review has proven highly effective in identifying relevant articles pertinent to the study. From the extensive literature surveyed, several critical parameters have emerged as pivotal for optimal Anaerobic Digestion (AD) process performance. These parameters encompass temperature, pH, Hydraulic Retention Time (HRT), Carbon/Nitrogen (C/N) ratio, sample preparation, and treatment procedures. It is advisable to adhere to average values for these identified parameters to enhance the efficacy of AD processes. Specifically, maintaining the temperature at 35 °C, pH at 6, HRT of 21 days, and Total Chemical Oxygen Demands (TCOs) above 8.5 COD/m³.d can significantly improve outcomes.

To further advance our comprehension and practical implementation, it is proposed that future studies focus on analyzing the efficiency of the suggested processes for each specific variable. Conducting practical experiments enable researchers to gain valuable insights into the impact of these parameters on biogas production and the overall process optimization. Overall, the findings from this bibliometric review offer valuable guidelines for optimizing AD processes, providing a foundation for further research and application in the field. By considering and fine-tuning these key parameters, we can enhance the efficiency and sustainability of biogas production, thereby contributing to a more environmentally friendly waste management solution.

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