Characterization of Sludge for Biogas Production Using Anaerobic Digestion: A Literature Review Approach

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This article conducts bibliographic research to characterize sludge for biogas production. The focus is on identifying key components such as organic matter, nutrients, pH, and chemical composition. Additionally, parameters such as the carbon/nitrogen ratio, inhibitory compounds, and biological activity are explored to assess their impact on anaerobic digestion performance. This bibliographic approach seeks to establish optimal parameter ranges for sludge utilization in biogas production. By comprehensively understanding the composition and properties of the sludge, this study contributes to enhancing the efficiency and effectiveness of anaerobic digestion processes.

Keywords: Sludge. Biogas. Anaerobic Digestion.

The process of globalization has significantly impacted the environment, presenting both challenges and opportunities. However, it has also facilitated increased interconnectivity between nations, fostering knowledge sharing to address global environmental issues. In 1995, the Conference of the Parties (COP) was established as an annual meeting for signatory countries of the United Nations Framework Convention on Climate Change (UNFCCC), with the primary objective of achieving greenhouse gas emissions neutrality in the atmosphere within a timeframe that allows for the natural adaptation of terrestrial ecosystems. Noteworthy accomplishments of the COPs include the adoption of the Kyoto Protocol in 1997, which currently boasts adherence from 192 countries, and adopting the Paris Agreement in 2015, with participation from 196 countries [1]. Implementing technological waste management and bioenergy recovery mechanisms is vital in mitigating greenhouse gas emissions and promoting the transition to a circular economy [2]. Among the various clean and renewable energy sources, biogas has emerged as a prominent contender. Biogas can be utilized in electric power generators and refined into biomethane, a promising alternative to conventional vehicular natural gas (CNG) for light vehicles and cargo transport trucks [3].

Biogas production is derived from a biological process known as anaerobic digestion (AD). This process involves the synergistic action of anaerobic microorganisms, whether strict or facultative, to decompose complex organic molecules present in waste, such as carbohydrates, proteins, and lipids, primarily resulting in the production of methane (CH_4) and carbon dioxide (CO_2) [4]. The AD process occurs in four phases: hydrolysis, where lipids, polysaccharides, and proteins are broken down; acidogenesis, where hydrolysis byproducts are transformed into more minor short-chain compounds like butyric, propionic, and acetic acids, alcohols, nitrogen oxides, hydrogen sulfide, hydrogen, and carbon dioxide; acetogenesis, where the acids from the the previous phase is further converted into one- or two-carbon atom acids like formic and acetic acids, hydrogen, and carbon dioxide; and finally, methanogenesis, where methane is produced through the activity of methanogenic archaea, utilizing the carbon present in the biomass. Figure 1 illustrates different sources of organic matter for biogas production.

To enhance the performance of the anaerobic digestion (AD) process, studies are undertaken to

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Figure 1. Sources of organic matter.

elucidate the influence of process parameters on the degradation of organic matter and biogas production. These parameters encompass temperature, pH, nutrients, and the Carbon/Nitrogen ratio. Moreover, endeavors are made to surmount inhibitory factors that impede anaerobic microorganism activity. The primary objective of these studies is to investigate the operational conditions of the AD process, ultimately aiming to maximize efficiency and biogas production. This article distinguishes itself by aspiring to conduct a comprehensive bibliographic study on global advancements in biogas production through anaerobic digestion, with a specific emphasis on inoculum development (sludge).

Materials and Methods

Anaerobic digestion is a widely acknowledged and sustainable approach for converting organic waste into valuable biogas. The effective operation of anaerobic digesters hinges upon various factors, prominently the characterization of sludge. Such characterization is pivotal in comprehending its composition and properties, which influence biogas production's efficiency and productivity.

The present study adopts a systematic approach to identifying and analyze pertinent literature sourced from diverse scientific databases, including but not limited to ScienceDirect, Scielo, Scopus, and Web of Science. Employing a search strategy encompassing keywords such as "co-digestion" and "biogas," this methodology not only enriches the research process but also bolsters the quality and reliability of the study's findings, thus contributing to the advancement of knowledge in the field of anaerobic digestion for sustainable biogas production.

The scarcity of studies unearthed on the topic of co-digestion and biogas within the selected databases underscores a gap in the existing literature. However, this paucity offers an opportunity to focus on a specific aspect, such as the role of sludge in achieving high-efficiency anaerobic digestion. By narrowing down the study's scope, it becomes feasible to delve deeper into this particular area and potentially furnish new insights or perspectives.

Results and Discussion

An essential aspect of sludge characterization involves determining its chemical composition. This encompasses analyzing the content of organic matter, nutrients, and trace elements in the sludge. Organic matter is a substrate for microbial activity during anaerobic digestion, while nutrients such as nitrogen and phosphorus are crucial for microbial growth and metabolism [5]. Moreover, trace elements, including iron, cobalt, and nickel, can be cofactors for specific enzymes involved in the anaerobic degradation process [6].

Physical characteristics of the sludge, such as particle size distribution, settleability, and moisture content, also significantly impact biogas production. Particle size distribution influences the accessibility of microorganisms to organic matter, thereby affecting the degradation rate. Well-settling sludge facilitates the practical separation of solids, ensuring efficient retention time and contact between biomass and substrate [7]. Additionally, the moisture content of the sludge influences the overall digestion process, with optimal moisture levels promoting microbial activity and gas production [8].

Furthermore, the microbial community present in the sludge plays a pivotal role in anaerobic digestion. The diversity, abundance, and metabolic capabilities of microorganisms profoundly impact the efficiency of biogas production. Various microbial groups, including hydrolytic, acidogenic, acetogenic, and methanogenic bacteria, collaborate synergistically to convert complex organic compounds into biogas [9]. Understanding the microbial community structure through molecular techniques like DNA sequencing can provide insights into microbial dynamics and aid in optimizing the digestion process [10].

The selection of the inoculum and substrate is a critical factor that significantly influences the performance of anaerobic digesters [11]. "Inoculum" refers to a specific set of bacteria selected from the ecosystem and introduced into the system, along with the initial quantity used during operation. The inoculum plays a vital role in reducing the lag phase of the system, which is the period during which microorganisms adapt to the environment before initiating multiplication. Utilizing an appropriate inoculum helps prevent issues related to the accumulation of substances that inhibit microbial development at different stages of anaerobic digestion. When the inoculum is well-suited to the substrate employed in the process, it establishes synergy more rapidly, leading to quicker stability in biogas production [11]. pH is one of the critical factors that significantly influences biogas production in anaerobic digestion when using sludge as the inoculum [12]. Research has demonstrated that pH variations can affect the system differently, as different groups of microorganisms respond diversely to pH changes. The optimal pH range for this process, as indicated by studies on chicken waste, is between 6.7 and 7.5. Methanogenic archaea, crucial for biogas production, are particularly sensitive and function best within this pH range.

Different pH levels will result in the production of specific compounds. Lower pH values lead to the production of acetic and butyric acids, while a pH close to 8.0 produces acetic and propionic acids [12]. The decomposition of organic matter in anaerobic digestion occurs through various phases, and facultative and strictly anaerobic microorganisms play vital roles in breaking down organic molecules of different complexities. These microorganisms form an ecosystem that can thrive in a balanced state without exposure to toxic environments [13]. Table 1 presents some characteristics, and Table 2 presents some properties of the aerobic digestion steps.

The pH control mechanism in anaerobic digestion is intricately linked to carbon dioxide (CO_2) and bicarbonate concentration. A significant decrease in pH prompts more CO_2 dissolution in the medium, while an increase in pH leads to CO_2 dissolving to form carbonic acid, subsequently releasing hydrogen [1]. Achieving pH control necessitates an appropriate ratio between intermediate alkalinity,

Table 1. Steps and characteristics of the aerobic digestion process [8].

Step	Characteristics
Hydrolysis	The AD process's initial phase involves converting complex organic matter, such as carbohydrates, proteins, and lipids, into simpler compounds like sugars, amino acids, and peptides. One material is converted into another through the action of exoenzymes excreted by hydrolytic fermentative bacteria.
Acidogenesis	The step is in which acidogenic fermentative bacteria convert organic matter from hydrolysis into several more straightforward products. These products include volatile fatty acids (VFAs), H_2, CO_2, acetate, glucose, alcohols, lactic acid, NH_3, and H_2S. These bacteria are called acidogenic because AGVs are the primary metabolic products they produce.
Acetogenesis	Acetogenic bacteria play a crucial role in the breakdown of products formed by acidogenic bacteria. These acidogenic bacteria are responsible for degrading at least 50 % of the biodegradable Chemical Oxygen Demand (COD), converting it into propionate and butyrate.
Methanogenesis	Methanogenic Archea plays a crucial role. Depending on the species, these Archea can use acetate to produce CH_4 and CO_2, or they can consume H_2 and CO_2 to form CH_4. In addition to these substrates, methanogenic Archeas can utilize formic acid, methanol, methylamines, and CO. Although they represent a smaller proportion of the other methanogenic Archea species, the acetoclastic are normally the predominant microorganisms in AD and are responsible for approximately 60 to 70 % of all CH_4 production.

provided by bicarbonate alkalinity, and partial alkalinity, determined by the alkalinity of volatile acids. This control mechanism facilitates the correction of pH fluctuations within the reaction [2].

The composition of nutrients in the inoculum is another critical consideration for anaerobic digestion. Anaerobic microorganisms rely on nutrients like phosphorus, nitrogen, and sulfur for proper digestion. The presence of sulfur ions, potassium, calcium, magnesium, chlorine, and sulfate is necessary for optimal microbial function [12]. Additionally, nutrients such as copper, iron, magnesium, molybdenum, vanadium, and zinc are essential for microbial growth. However, specific ions like Cu^{++}, Zn^{++}, alkali metal, alkaline earth metal ions, and NH_4^+ can act as inhibitors [12]. Sulfur compounds may precipitate nutrients, resulting in harmful copper, iron, molybdenum, and nickel levels.

The Carbon/Nitrogen (C/N) ratio is a crucial aspect of substrate composition, directly impacting biogas production and forming desirable bacterial cells. An ideal C/N ratio falls between 20 and 35, ensuring a balanced environment. Carbon molecules in the substrate play a pivotal role in methane formation. However, a high C/N ratio may impede bacterial cell renewal and formation due to limited nitrogen availability. Conversely, a low C/N ratio combined with excessive ammonium (NH_4) can create a toxic environment for the microbial community during anaerobic digestion. Furthermore, the presence of nitrite significantly affects the substrate solubilization, hydrolysis, and organic acidification due to its redox properties.

Temperature is another influential factor affecting microbial growth, sludge characteristics,

Table 2. Characterization of inhibitors.

Operational Conditions	Characteristics	Reference
Temperature (°C)	25-35 hydrolysis	[12]
	25-35 acidogenesis	
	32-42 methanogenesis	
ph	6.7-7.5	[11]
C:N	Hydrolysis and Acidogenesis 10-45	[12]
	Methanogenesis 20-30	
S	1-25 mg S\L	[14]
Temperature for growth of microorganisms	Thermophiles 60°C	[12]
	Mesophilic 37°C	
	Psychrophiliacs 15°C	
AI/AP Ratio	Overload reactor >0.4	[12]
	Optimal Range 0.3-0.4	
	Underload reactor <0.3	

substrate solubility, and ionic balance. Bacterial growth and metabolic activity are temperature-dependent, influencing the quantity and types of biogases produced [15]. Light metal ions, such as calcium, magnesium, potassium, and sodium, are also prevalent in anaerobic digestion. These ions can be released during organic matter degradation or utilized for pH adjustment and microbial growth [10]. However, their effects can vary based on concentration, potentially inhibiting or delaying growth and exhibiting toxicity towards the inoculum. Table 3 presents an overview of metals in aerobic digestion and their causes and effects [10].

Indeed, sludge characterization is indispensable for biogas production through anaerobic digestion. We examined sludge's chemical composition, physical attributes, and microbial composition, yielding crucial insights for optimizing processes, formulating substrates, and controlling operations. This understanding of sludge's distinct features empowers operators and researchers to improve the efficiency and reliability of anaerobic digesters, thereby maximizing biogas production from organic waste.

Conclusion

Sludge characterization is a pivotal aspect in the quest for efficient biogas production through anaerobic digestion. Through meticulous research and analysis, we have garnered invaluable insights into the requisite attributes of sludge and refined its utilization. Our findings underscore the imperative of conducting a comprehensive assessment of sludge, considering factors such as pH, nutrient composition, and temperature. The pH level of sludge profoundly influences the phases and metabolic processes of microorganisms engaged in biogas production. A nuanced understanding of pH requisites and their interplay with acidogenesis is paramount for optimizing biogas yield. Moreover, the availability of essential nutrients, notably carbon and nitrogen, assumes critical significance as they serve as sustenance for microbial

Table 3. Light metal ions, causes, and effects [10].

Metal ions	Causes	Effects
Aluminum	Competition with iron and manganese or their adhesion to the microbial cell membrane or cell wall.	It may affect microbial growth.
Calcium	Carbonate and phosphate precipitation.	Fouling reactors and pipes, fouling biomass, reducing methanogenic activity, losing buffering capacity and essential nutrients for anaerobic degradation.
Magnesium	Stimulate the production of individual cells.	Inhibition of the growth of microorganisms, loss of acetoclastic activity.
Potassium	Passive influx of potassium ions that neutralize the membrane potential, extractors for metals bound to exchangeable sites in the sludge.	The most pronounced inhibitory effect is in the thermophilic temperature range.

populations. A balanced ratio of these nutrients is indispensable for fostering optimal microbial activity. Excessive nutrient levels can precipitate the accumulation of free ammonia, impeding reactions and hampering biogas production. Temperature emerges as a pivotal determinant in microbial proliferation and activity. Maintaining an optimal temperature range supports robust microbial function, ensuring efficient biogas generation. Vigilant monitoring and stringent temperature control throughout the anaerobic digestion are imperative for nurturing stable microbial communities and fostering biogas production. To uphold the standards of high-quality biogas production, meticulous sludge analysis prior to commencing anaerobic digestion is imperative. Furthermore, continuous monitoring throughout the reaction period is indispensable to evaluating and upholding desired production parameters. By steadfastly implementing these measures, we can augment the efficiency and efficacy of biogas production, heralding a transition towards a more sustainable and renewable energy paradigm.

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