Uluslararası İleri Doğa Bilimleri ve Mühendislik Araştırmaları Dergisi
Sayı 8, S. 43-57, 4, 2024
© Telif hakkı IJANSER'e aittir
Araştırma Makalesi

IJANSER
https://as-proceeding.com/index.php/ijanser
ISSN: 2980-0811

International Journal of Advanced Natural Sciences and Engineering Researches
Volume 8, pp. 43-57, 4, 2024
Copyright © 2024 IJANSER
Research Article

Biogas: A Sustainable Energy Solution for Reducing Greenhouse Gas Emissions

Sümeyye Arslan [1*], Zehra Gülten Yalçın[1], Mustafa Dağ[1]

[1]*Department of Chemical Engineering, Faculty of Engineering, Çankırı Karatekin University, 18100, Çankırı, Turkey.*

(Received:02 May 2024, Accepted: 10 May 2024)

(3rd International Conference on Engineering, Natural and Social Sciences ICENSOS 2024, May 16-17, 2024)

ATIF/REFERENCE: Arslan, S., Yalçın, Z. G. & Dağ, M. (2024). Biogas: A Sustainable Energy Solution for Reducing Greenhouse Gas Emissions. *International Journal of Advanced Natural Sciences and Engineering Researches*, 8(4), 43-57.

Abstract – One of the greatest challenges that societies face now and in the future is the reduction of greenhouse gas emissions to mitigate climate change. Therefore, the preference for biogas over fossil fuels is crucial. Biogas can be produced from various organic waste streams or as a byproduct of industrial processes. It offers several advantages, including not only energy production but also the decomposition of organic waste through anaerobic digestion, mitigation of odor emissions, prevention of pathogen release, among others. Additionally, the nutrient-rich digested residues can be used as fertilizer for recycling nutrients back into fields. However, the quantity of available organic materials for biogas production is limited. Hence, there is a need for new substrates and advanced technologies for biogas production worldwide. Significant advancements have been made in addressing these limitations through the utilization of lignocellulosic biomass, the development of high-rate systems, and the application of membrane technologies in the anaerobic digestion process. The breakdown of organic matter requires synchronized movement of different groups of microorganisms with varying metabolic capacities. The unsustainable use of fossil fuels underscores the environmental impact of greenhouse gases, prompting research into renewable energy production from organic sources and waste. Global energy demand is high, with the majority being derived from fossil sources. Recent studies highlight anaerobic digestion as an efficient alternative that combines biofuel production with sustainable waste management. Technological research efforts are ongoing to enhance biogas production and quality within the biogas industry.

Keywords – Biogas, Greenhouse Gas Emissions, Anaerobic Digestion, Renewable Energy

1. INTRODUCTION

Anaerobic digestion (AD) for biogas production is a process that utilizes organic waste generated worldwide, leading to positive environmental impacts. Industrial and municipal wastewater, along with agricultural, urban, and food industry waste, as well as plant residues, can be treated using this method. It offers advantages over many waste treatment methods. The primary product of the treatment, biogas, is a renewable energy source, while the residual digestate left over can be used as fertilizer for plants. The performance of the AD process largely depends on the characteristics of the raw material and the activities of microorganisms involved in the various stages of degradation. The continuous use of fossil fuels and the environmental impact of greenhouse gases (GHGs) have prompted research into alternative fuel production from biological sources. The amount of greenhouse gas emissions in the atmosphere is increasing, with carbon dioxide (CO_2) contributing the most to this increase. Biogas derived from waste and residues will play a critical role in future energy scenarios. Biogas is a highly versatile renewable energy source that can replace traditional fuels for heat and power generation [1,2].

2. BIOGAS INDUSTRY IN EUROPE

Due to environmental, economic, and social reasons, the interest in bioenergy is rapidly increasing worldwide. Biogas contributes significantly to sustainable and renewable energy. In Europe, biogas facilities are categorized based on the type of substrates treated or the size of the facility. There isn't much difference in terms of technological activities between facilities based on these two characteristics. A biogas facility is a site where anaerobic digestion occurs. It consists of five main sections:

- Substrate management area
- Feeding area
- Anaerobic digestion area
- Gas storage area
- Digestate storage area

The substrate management area stores biogas substrates consisting of renewable sources such as animal manure, organic waste, corn, and grass silage. These undergo "four stages of degradation," with methane produced in the final stage. The gas storage facility will store the produced methane or biogas until needed. Typically, the gas will be sent to a combined heat and power (CHP) facility where it will be converted into electricity and heat.

3. WASTE PROCESS FOR BIOGAS PRODUCTION

3.1 raw materials

Various types of waste can be used as substrates for biogas production using anaerobic digestion technology. Large amounts of lignocellulosic waste are collected from agricultural, urban, and other activities. The types of waste commonly used in the European energy industry include:

- Animal manure and slurries
- Sewage sludge
- Municipal solid waste
- Food waste

Table 1. Production Quantities and Potentials for Different Feedstocks for Biogas Production [3,4]

Type	Biogas Yield per Ton of Matter	Produced Electricity (kWh)
Cattle Manure	55-68	122.5
Poultry Litter/Manure	126	257.3
Pig	826-1200	1687.4
Food Waste	110	224.6
Fruit Waste	74	151.6
Horse Manure	56	114.3
Corn Waste	200/220	409.6
Municipal Solid Waste	101.5	207.2
Swine Slurry	Kas.25	23.May
Sewage Sludge	47	96

Biomass encompasses carbohydrates, proteins, fats, cellulose, and hemicellulose, which serve as raw materials for biogas production. Co-substrates are utilized to increase the organic content, thereby achieving higher gas yields. Commonly employed co-substrates include agricultural organic wastes, food wastes, and urban biogenic wastes. Pretreatment is necessary for the composition of biogas. The application of pretreatment methods enhances substrate degradation and, consequently, process efficiency. Chemical, mechanical, or enzymatic processes can be applied to enhance degradation, although this does not necessarily result in higher biogas yields [5,6,36,37].

3.2 Lignocellulosic Molecular Components

Cellulosic wastes such as energy crops, agricultural residues, and sewage sludge hold significant potential for biofuel production.

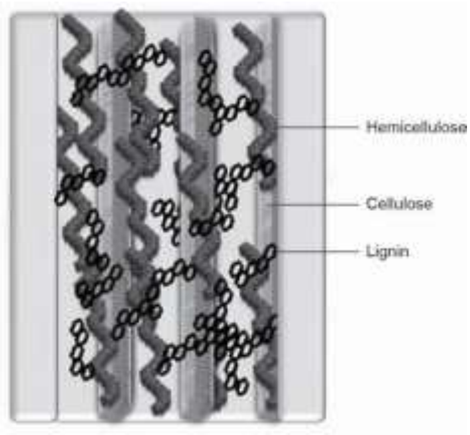

Figure 1. Diagram of the Main Components of Lignocellulose [7]

The three main components of lignocellulose are depicted in Figure 1. These are cellulose, hemicellulose, and lignin. Cellulose serves as the primary structural component related to the mechanical strength of plant cell walls, while hemicellulose macromolecules are synthesized through the repetition of pentose polymers.

Table 2. Comparison of Biogas Yield and Electricity Generation from Different Potential Substrates Layers [3,4]

Type	**Biogas yield per ton fresh matter (m^3)**	**Electricity produced per ton fresh matter (kW.h)**
cattle dung	55-68	122,5
chicken litter/dung	126	257,3
fat	826-1200	1687,4
food waste (disinfected)	110	224,6
fruit wastes	74	151,6
horse manure	56	114,3
maize silage	200/220	409,6
municipal solid waste	101,5	207,2
pig slurry	11-25	23,5
sewage sludge	47	96

Lignin contains three aromatic alcohols (coniferyl alcohol, sinapyl alcohol, and p-coumaryl alcohol) produced through a biosynthetic process. The presence of lignocellulose in various forms depends on factors such as season, origin, material, and composition. According to Deguchi et al., crystalline cellulose can be converted into irregular cellulose structures under conditions of 320°C temperature and 25 MPa pressure. Cellulose is the most abundant compound on Earth, constituting over 25% of plant biomass. Hemicellulose is a complex and variable structure composed of different polymers, including pentoses (xylose, arabinose), hexoses (mannose, glucose, and galactose), and sugar/uronic acids (glucuronic, galacturonic, and methylgalacturonic acids) [8,9,10].

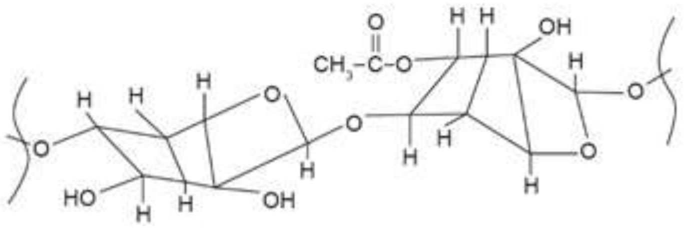

Figure 2. Molecular Chain Structure of Hemicellulose [10]

Hemicellulose possesses low molecular weight and short side chains, consisting of numerous sugars easily hydrolyzed in polymer structures. It forms a bond between lignin and cellulose molecules, thereby increasing the compactness of the entire cellulose-hemicellulose-lignin network. The solubility of different hemicellulose compounds is directly related to temperature. Due to the unknown melting points, the solubility of high molecular weight polymers is unpredictable. Boblet reports that hemicellulosic compounds begin to dissolve in water at 180°C in a neutral environment. Garrote et al. mention hemicellulose dissolving at 150°C. This dissolution is dependent on various parameters, including pH, temperature, and moisture content. Bobleter also states that lignin dissolves in water at 180°C in a neutral environment, similar to hemicellulose. The solubility of lignin in acidic, neutral, or alkaline environments is associated with the presence of phenylpropane-based units in lignin. While agricultural residues and grasses contain 5-30% lignin, crop residues mainly consist of hemicellulose. Studies have shown that the properties of lignin affect the results of hydrolysis [11,12].

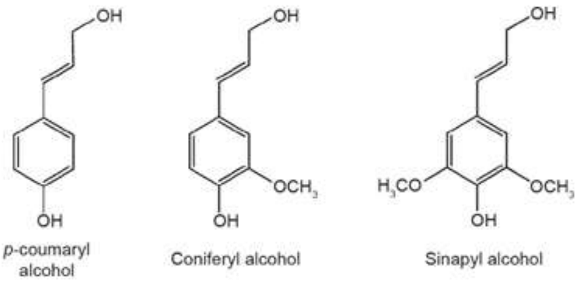

Figure 3. Basic Structure of Lignin [10]

4. CURRENT TRENDS IN BIOGAS PRODUCTION

4.1 Challenges and Solutions in the Utilization of Lignocellulosic Waste for Biogas Production

While lignocellulosic waste holds promise for biogas production, its complex structure poses challenges for the operation of biorefineries. The components of lignocellulose (cellulose, hemicellulose, and lignin) strengthen bonds between molecules, resulting in a compact and robust structure. Recent evaluations indicate that pretreatment performance affects biogas efficiency.

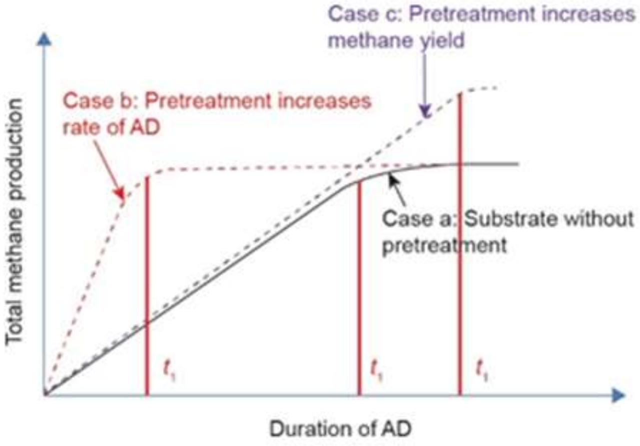

Figure 4. Graph of Total Methane Production vs. AD Duration [10]

Pecorini et al. reported that autoclaving and microwave treatments result in the hydrolysis of significant portions of non-biodegradable materials in municipal waste, enhancing anaerobic digestion efficiency. Micolucci et al. achieved higher biogas yields by subjecting biomass to extensive pressing as a pretreatment step. Ideal biomass pretreatment aims to break down the raw material into fermentable sugars, eliminating lignin resistance and reducing the crystalline structure of cellulose to make the substrate more accessible to microorganisms. However, challenges related to degradation remain unresolved [13,14,38].

4.2 Multi-purpose and High Pressure AD

To enhance AD efficiency, several projects have been developed, suggesting that separating the hydrolysis/acidogenesis and acetogenesis/methanogenesis stages into separate reactors could increase the conversion rate of organic matter to methane. However, this approach carries a significant disadvantage due to its high cost.

The implementation of multi-bioreactor systems generally aims at improved process stability and higher efficiency. A multi-stage bioreactor system allows for the application of different conditions. Multi-stage AD is used for commercial biogas fuel production. Colussi et al. investigated two-stage AD of corn, resulting in higher chemical oxygen demand removal efficiency and higher biogas yield [15]. Marin Pérez and Weber reported that physically dividing AD into two stages allowed for the exposure of different process conditions for specific bacterial species, accelerating hydrolysis (the rate-limiting step) and leading to faster organic matter breakdown. Yabu et al. examined two-stage AD of garbage along with ammonia stripping to prevent ammonia inhibition [17]. Park et al. compared single and two-stage AD of kitchen waste, finding that two-stage AD resulted in higher methane yield [18].

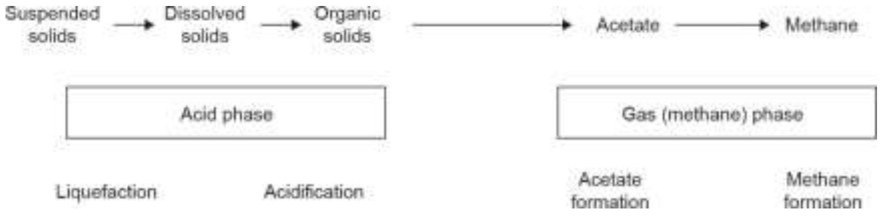

Figure 5. Standard Multi-stage AD [16]

A two-stage AD process can be applied to various wastes, affecting high microbiological activity. Blonskaja et al. used a two-stage system to process distillery wastes, observing a higher growth rate in methanogenic populations, resulting in increased gas production [19].

Nasr et al. investigated bio-hydrogen production from sewage sludge and concluded that a two-stage system enhances the performance of the AD process.

A possible technique based on high working pressure (up to 100 bar, 1 bar = 100 kPa) has been developed, enabling the production of biogas with over 95% methane content. The goal of this technique is to integrate biogas production and on-site high-pressure purification into a single process to produce clean biogas (>99% methane) that can be directly fed into natural gas grids [20,21].

4.3 Microbial Ecology: Dynamics of Microbiology

The conversion of most waste products such as pentoses, hexoses, volatile compounds, and soluble lignin into methane is possible through the improvement of AD using a microbial consortium. Carbohydrates, fats, and proteins are hydrolyzed into sugars, fatty acids, and amino acids, respectively. These compounds with smaller carbon chains are then converted by acidogenic bacteria (acidogens) into a mixture of other small products such as volatile fatty acids (VFAs) and alcohols. Acetogenic bacteria (acetogens) subsequently convert VFAs into important substrates for biogas production, namely acetic acid (acetate),

CO_2, and hydrogen. Finally, methanogens produce biogas. The interactions of different microbial groups vary in quantity and affect the overall process reaction rate [22].

5. CURRENT ISSUES IN BIOGAS PRODUCTION

5.1 The Gap between Biotechnology Research and Commercialization

Large-scale biogas production from lignocellulosic biomass has a significant impact, and progress studies are still ongoing. These processes typically face technical challenges stemming from a lack of understanding of optimal reactor operation. Research in this field aims to facilitate and advance the implementation of AD. The key to defining bioindustry and research lies in understanding science and technology and evaluating the effects of significant technical, economic, and ecological barriers. Benefits and costs must be analyzed. For instance, to reduce costs, it is necessary to identify critical technological steps (e.g., the cost of implementing multi-stage AD or enzyme usage) that have the greatest impact on the overall economy. Analysis of such steps will provide valuable insights for assessing research priorities for development. The type and quantity of microorganisms breaking down organic waste, as well as the conversion rates of biocatalysts, affect process stability. High production costs increase the cost of biogas. The aim is to develop enzymes with good activity performance. AD technology also requires electricity and heat [23].

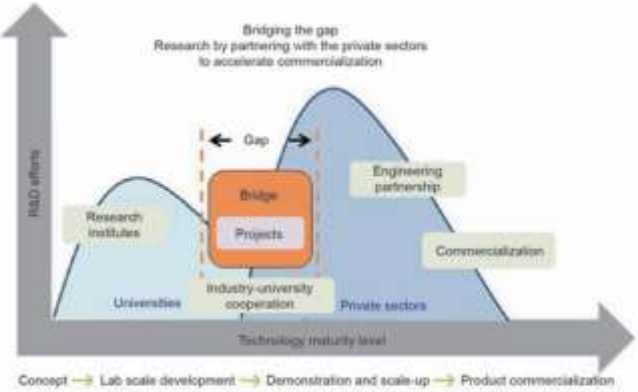

Figure 6. Bioindustry Research Scheme [23]

Optimizing the combination of these parameters signals cost-effective biogas production. Research can play a catalytic role in bridging the gap between engineering and biology/biotechnology to provide innovative and sustainable technological alternatives for the biogas sector.

Table 3. Current Challenges and Future R&D Studies [23]

Issues	**R&D Studies**
Use of enzymes, bacteria, or catalysts	- Expanding application range - High production cost
Service requirements	- Electricity consumption - Excess of oxygen and hydrogen - High pressure and heat
Technology	- Pre-treatment - Multi-stage technology - Advanced techniques (high pressure) - Micro-scale technology
Fuel properties	- Enriched methane biogas - Less hydrogen sulfide

5.2 The Future of Biogas in Circular/Green Economy

The economics of biogas are associated with factors such as waste availability and logistics, process efficiency, and final product properties. Anaerobic digestion technology has been proven and has gained commercial significance. There is a wide variety of lignocellulosic waste available at low cost and high availability that can be processed for biogas production. Challenges related to biogas utilization; therefore, the need to modify engines for biogas combustion should be considered [24,25].

6. Drivers of Biogas Production

6.1 Co-Digestion Strategy

Anaerobic digestion (AD) of a mixture consisting of two or more substrates simultaneously is referred to as co-digestion. Due to the different characteristics of the co-digested wastes, co-digestion can enhance the performance of the AD process by providing a balanced nutrient source and sometimes increasing the necessary moisture content in the digestion environment through positive energy generated in the digestion process.

Following the AD process, the digested residue is typically transferred to storage tanks covered with a gas-impermeable membrane to recover the remaining gas and prevent methane leakage into the atmosphere. The digested residue is rich in nutrients and can therefore be recycled back to fields as fertilizer. The produced biogas is utilized as a renewable energy source, with biogas being preferred for heat and electricity in Europe. Some of the generated heat is used for process heating in the biogas plant, while the remaining heat is conveyed to consumers through district heating systems. The produced electricity is sold to the grid. In some countries like Sweden, the produced biogas is converted into bio-methane used as vehicle fuel. In recent years, co-digestion has been observed to increase AD efficiency, and studies have focused on methane yield. As a result of these studies, an increase in methane gas potential of up to 43% has been observed. The examined substrates include:

- Slaughterhouse waste
- Crop residues
- Manure waste fractions
- Urban waste fractions

Successful digestion and process stability for biogas production depend on waste composition and microbial groups. Additionally, co-digestion results in low methane gas yield due to antagonistic interactions [26].

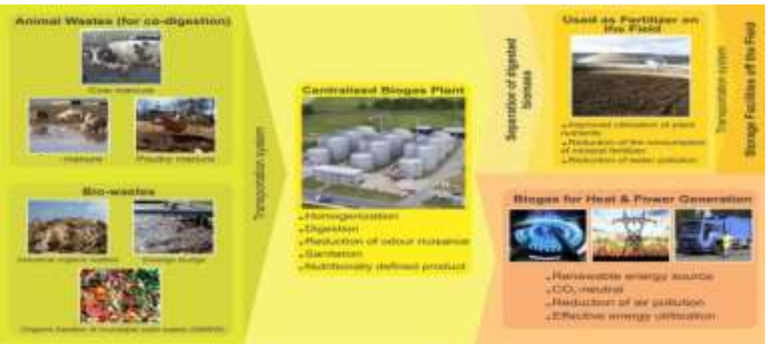

Figure 7. Main Process Flow Diagram of a Centralized Biogas Plant [26]

6.2 Farm-Scale Biogas Plants

The primary substrate fractions utilized in farm-scale biogas plants are animal manure and energy crops. Organic waste presents the closed-loop of AD and outlines the key steps in quality management processes. The most common and recent digester type used in farm-scale applications is typically a vertical tank made of concrete, equipped with a flexible membrane and a lightweight roof, enabling its utilization in a digested state [27].

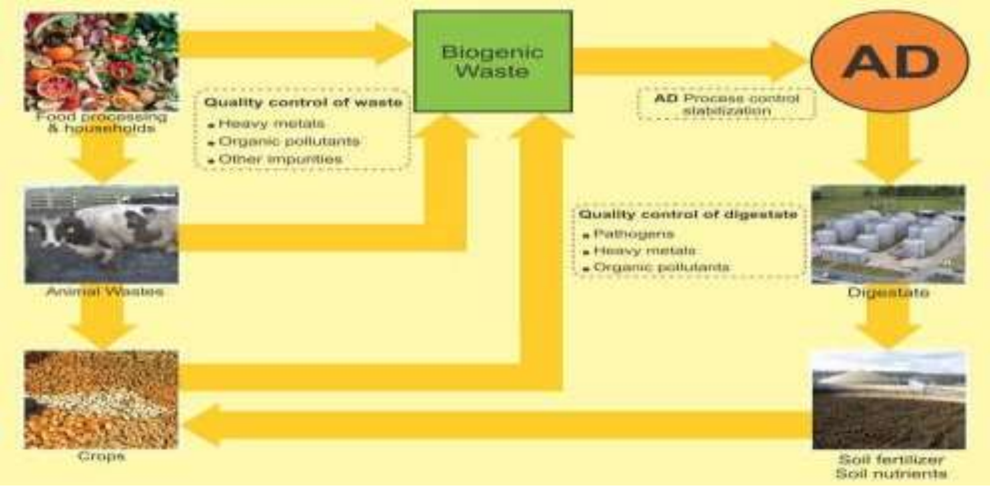

Figure 8. Diagram of the Closed Loop of Anaerobic Digestion of Organic Wastes and Quality Management Process [26]

7. Current Biogas Process Technologies

7.1 Biogas Production via Anaerobic Digestion (AD)

Anaerobic digestion (AD) offers significant advantages compared to many other methods. In fact, it has been defined as one of the most energy-efficient and environmentally beneficial technologies for bioenergy production. The degradation process can be divided into four stages:

- Hydrolysis
- Acidogenesis
- Acetogenesis
- Methanogenesis

Each stage involves different and essential microbial communities.

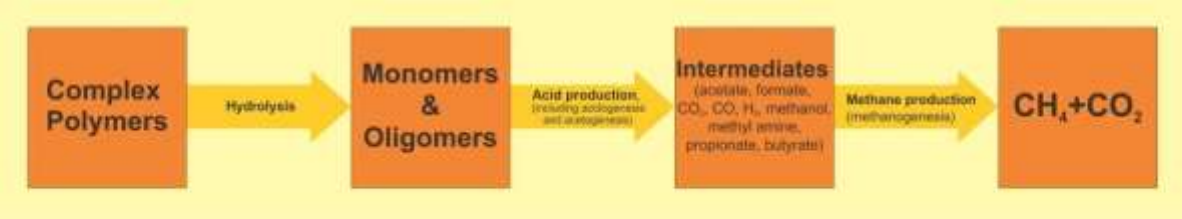

Figure 9. Stages of degradation process during AD [29]

In addition to energy production, anaerobic digestion offers other advantages such as the breakdown of organic waste, reduction of odor emissions, and lowering of pathogen levels. Moreover, the nutrient-rich digested residue can be utilized as organic fertilizer for cultivable lands and as an organic substrate for greenhouse cultivation. Urban solid waste (MSW) originates from agricultural waste and industrial activities. MSW mainly consists of food waste, paper and cardboard, garden clippings, wood, plastics, metals, and glass. However, its composition varies according to the regions and countries from which it is collected. For this fraction to be used in biogas production, all inert materials including plastics, metals, and glass must be removed prior to AD.

Food processing industries also generate waste, the quantity of which is not specified as it largely depends on the industry and the technology employed. For instance, up to 50% of processed fruit in the fruit juice production industry becomes waste. Additionally, about 30% of a chicken's weight is unsuitable for human consumption and is discarded as waste during slaughter and other processing steps. While all these different waste fractions are suitable for biogas production, their biogas potentials vary significantly [28,29]

7.2 Pre-treatment for Enhanced Biogas Production

The limited availability of fossil fuels, fluctuating energy prices, and environmental concerns coupled with increasing global energy demand necessitate the use of renewable energies. Currently used feedstocks for AD are limited, and therefore, the abundance and availability of lignocellulosic biomass worldwide, coupled with their high carbohydrate content, make these materials attractive raw materials for biofuel production. Lignocellulosics constitute approximately 50% of the world's biomass, and lignocellulosic production can reach up to about 200 billion tons annually.

In the first step of AD, namely the hydrolysis step, hydrolytic bacteria convert insoluble complex organic matter into monomers. As a result of human activities, large amounts of organic solid waste emerge that could serve as raw material for biogas production. Depending on their source, different waste streams can be classified and contain soluble oligomers such as fatty acids, amino acids, and sugars (see Figure 9). The enzymes involved in this process include cellulases, hemicellulases, lipases, amylases, and proteases. Therefore, biogas processes can hydrolyze any substrate. The rate of hydrolysis depends on certain criteria, including whether the required enzymes are produced by microorganisms and if adequate surface area is provided for physical contact between enzymes and substrates, hydrolysis can progress relatively quickly. Additionally, substrates that are more resistant, such as cellulose, require longer times for breakdown, and complete breakdown may not occur. Therefore, such substrates exhibit rate-limiting characteristics in hydrolysis. Hence, a pre-treatment step is required to prevent enzymatic and microbiological degradation. A suitable pre-treatment through disruption of the secondary cell wall structure will reduce the biomass resistance and thus facilitate subsequent processes. Ideally, a pre-treatment should also be cost-effective and provide a substrate rich in polysaccharides with limited amounts of inhibitory by-products [28,30].

7.3 Challenges of Current Processes

The anaerobic digestion (AD) of organic matter requires several different groups of microorganisms with varying metabolic capacities to work together. To achieve a stable biogas process, all conversion steps involved in the breakdown of organic matter and the microorganisms performing these steps must work synchronously. Methanogens have longer replication times and are generally considered the most sensitive group to process disturbances. Therefore, it is important to prevent the separation of these microorganism groups from the system by differentiating between the solid retention time (SRT) and the hydraulic retention time (HRT).

8. New Anaerobic Digestion Technologies

In recent times, anaerobic digestion (AD) systems have evolved in various forms to enhance process efficiency. Overcoming methanogenesis as the rate-limiting step, and effectively retaining slow-growing methanogenic biomass, has been a significant challenge. A pivotal breakthrough has been the development of a new reactor design known as the Upflow Anaerobic Sludge Blanket (UASB) reactor, which contains a well-settling methanogenic sludge due to the formation of a dense sludge bed. Another technology facilitating the retention of active biomass within the system is the application of Membrane Bioreactors (MBRs) [5].

8.1 High-Rate Anaerobic Reactors

Developed in the early 1970s in the Netherlands, the Upflow Anaerobic Sludge Blanket (UASB) reactor is perhaps the most popular high-rate reactor system applied for anaerobic biological treatment of "wastewater," with over 1000 UASB reactors operating worldwide. This process is attractive due to its compactness, high loading rates, relatively short retention times for anaerobic treatment, low operational costs, low sludge production, and high methane production rates. Granular or flocculent sludge is a key distinguishing feature of these reactors compared to other anaerobic technologies. Therefore, a modified reactor configuration has recently been proposed aiming to separate hydrolysis and acidogenesis steps from methanogenesis by employing a two-stage process involving a continuously stirred tank reactor (CSTR) and a UASB reactor while treating MSW [31].

8.2 Anaerobic Bioreactors (An.ABR)

In Membrane Bioreactors (MBRs), membranes form a selective barrier allowing some components to pass while retaining others, thus safeguarding the biological system. The implementation of MBRs facilitates an increase in the Solid Retention Time (SRT) by preventing cell washout and a reduction in inhibitor concentrations through the separation of inhibitors. Currently, two different designs are applied for membrane bioreactors. The membrane can be placed in an external loop or submerged inside the reactor.

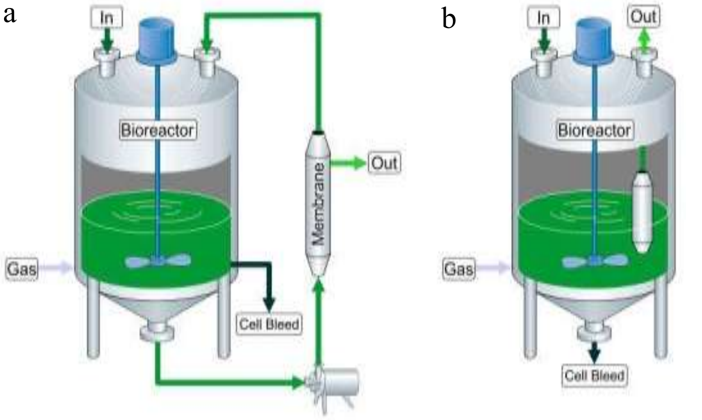

Figure 10. Bioreactor membrane designs, a) External loop, b) Submerged loop [32]

Less energy is required in the submerged loop due to no need for energy input to maintain continuous flow within the system. However, operating this system at high particle and/or cell concentrations may pose challenges due to fouling.

Membrane technologies developed and applied in wastewater treatment processes can also be utilized for biogas production processes. Various studies have been conducted on membrane technologies in biogas systems. For instance, encapsulation of methane-producing bacteria has been performed to assess the applicability of this technique to biogas processes. Alginate microcapsules were obtained using a single-step liquid droplet formation method. Ca^{2+} carboxymethyl was used as the counter ion against alginate. Additionally, a synthetic Durapore membrane (hydrophilic polyvinylidene fluoride (PVDF)) was tested by making encapsulation pouches of 3-3 or 3-6 cm^2 dimensions to retain bacteria. The results showed that these membranes allow nutrient penetration to the cells while the produced gas can diffuse out of the capsules. The inhibitory effects on biogas-producing microorganisms pose challenges to biogas processes. The results, demonstrating the protective effect of the PVDF membrane, resulted in faster biogas production by encapsulated bacteria compared to free cells.

The recalcitrant structure of lignocellulosic biomass complicates its use in biogas processes. In addition to using different pretreatment technologies before AD to open their chemical structures, another theory has recently been proposed aiming to obtain synthesis gas called syngas by thermochemical processing of lignocellulosic biomass. Syngas primarily contains carbon monoxide (CO), hydrogen (H_2), and carbon dioxide (CO_2g). Therefore, this gas mixture can be used by anaerobic microorganisms to produce methane using CO and/or CO_2 as a carbon source and H_2 as an energy source. To increase the productivity and efficiency of conversion, a reverse Membrane Bioreactor (RMBR) holding the cells inside the reactor has been applied. Using anaerobic sludge coated with PVDF (hydrophilic polyvinylidene fluoride) membranes, the conversion of syngas to methane was achieved within a detention time of 1 day [33,34].

9. Microbial Community Analysis and Biogas Process Control

As mentioned, AD involves different degradation steps facilitated by various groups of microorganisms, including hydrolysis, acidogenesis, acetogenesis, and methanogenesis. These microorganisms can be categorized into three functional groups:

- Hydrolytic bacteria
- Fermentative bacteria
- Obligate hydrogen-producing acetogenic bacteria
- Methanogenic archaea

Hydrolytic acidogenic bacteria (HABs) hydrolyze complex organic polymers into simple compounds during the initial stage of degradation. Volatile fatty acids (VFAs), alcohols, H_2, and CO_2 are produced during the acidogenesis process. Similarly, acetic acid, H_2, and CO_2 are produced during the acetogenesis step by obligate H_2-producing acetogens. Butyrate-utilizing acetogens represent the majority of acetogens. An important detail in degradation is that anaerobic oxidation of butyrate and propionate occurs only in syntrophic association with H_2-utilizing methanogens (HUMs), consuming H_2 and CO_2 for methane (CH_4) production and preventing the accumulation of increasing H_2 pressure in the digester. Another pathway for methane formation is the conversion of acetate to CH_4 and CO_2 by acetate-utilizing methanogens (AUMs). Molecular biology techniques are crucial for understanding microbial communities and their interactions with AD, leading to a more efficient biogas production process [35].

10. Result

The increasing demand for renewable energy has led to the exploration of new substrates and the development of new technologies for biogas production. When it comes to feedstocks for Anaerobic Digestion (AD), the preference is for waste materials, as this approach addresses both waste reduction and energy generation. While lignocellulosic residues are readily available, further research is needed to advance economically viable processes through new pre-treatment technologies.

The anaerobic decomposition of organic matter requires a well-functioning microbial process, and it is known that methanogenic microorganisms responsible for methane production in the final step of digestion are the most sensitive to process disturbances. This necessitates the advancement of new process configurations aimed at preventing their removal from the system, in addition to their slow growth rates. In this regard, the development of Upflow Anaerobic Sludge Blanket (UASB) reactors has been a significant milestone. The formation of dense, well-settling granular sludge in the UASB system enables effective separation of Solid Retention Time (SRT) and Hydraulic Retention Time (HRT).

To put it succinctly, a critical factor for successful anaerobic high-rate treatment is the retention of all slow-growing microorganisms. Therefore, in cases where sludge granulation is hindered or incomplete, membranes can be applied for biomass separation and recycling to the reactor. Consequently, the approach to using different membrane configurations stems from the need to enhance efficiency. However, in conditions of high particle and/or cell concentrations, the operation of such a system may be problematic due to fouling. Therefore, the full-scale application of Anaerobic Membrane Bioreactor (AnMBR) technology will be largely dependent on flow levels achieved during long-term operation.

Finally, as AD is a complex microbial process, various projects have been undertaken recently to understand the relationship between microbial community structure, operating conditions, and process performance. By utilizing newly developed molecular biology tools, it will be possible to effectively control and regulate the process. While these techniques have primarily been applied to the digestion step itself thus far, in the future, a more precise approach should be taken to the entire biogas production system, including post-digestion steps such as storage and feeding.

11. References

[1] Wang, H., Vuorela, M., Keränen, A-L., Lehtinen, T.M., Lensu, A., Lehtomäki, A., Rintala, J., 2010. Development of microbial populations in the anaerobic hydrolysis of grass silage for methane production. FEMS Microbiol. Ecol. 72(3), 496-506.

[2] Batstone, D.J., Keller, J., Angelidaki, I., Kalyuzhnyi, S.V., Pavlostathis, S.G., Rozzi, A., Sanders, W.T.M., Siegrist, H., Vavilin, V.A., 2002. The IWA Anaerobic Digestion Model No 1 (ADM 1). Water Sci. Technol. 45(10), 65-73.

[3] Stucki M, Jungbluth N, Leuenberger M. Life cycle assessment of biogas production from different substrates. Final report. Bern: Federal Department of Environment, Transport, Energy and Communications, Federal Office of Energy; 2011 Dec.

[4] Sustainable Energy Authority of Ireland. Gas yields table. Dublin: Sustainable Energy Authority of Ireland; 2002

[5] ATV-DVWK. Thermische, chemische und biochemische Desintegrationsverfahren: 3. Arbeitsbericht der Arbeitsgruppe AK-1.6 “Klärschlammdesintegration”. Corresp Wastewater 2003;50:796–804. Germany.

[6] Mshandete A, Björnsson L, Kivaisi AK, Rubindamayugi MST, Matthiasson B. Effect of particle size on biogas yield from sisal fibre waste. Renew Energy 2006;31(14):2385–92

[7] Philbrook A, Alissandratos A, Easton CJ. Biochemical processes for generating fuels and commodity chemicals from lignocellulosic biomass, environmental biotechnology. In: Marian P, editor New approaches and prospective applications. Rijeka: InTech; 2013. p. 39–64.

[8] Calvo-Flores FG, Dobado JA. Lignin as renewable raw material. ChemSusChem 2010;3(11):1227–35

[9] Menon V, Rao M. Trends in bioconversion of lignocellulose: Biofuels, platform chemicals & biorefinery concept. Pror Energy Combust Sci 2012;38(4):522–50.

[10] Ratnaweeraa DR, Saha D, Pingali SV, Labbé N, Naskar AK, Dadmun M. The impact of lignin source on its self-assembly in solution. RSC Adv 2015;5(82):67258–66.

[11] Fengel D, Wegener G. Wood: Chemistry, ultrastructure, reactions. Berlin: De Gruyter; 1984.

[12]] Bobleter O. Hydrothermal degradation of polymers derived from plants. Prog Polym Sci 1994;19(5):797–841.

[13] Pecorini I, Baldi F, Carnevale EA, Corti A. Biochemical methane potential tests of different autoclaved and microwaved lignocellulosic organic fractions of municipal solid waste. Waste Manag 2016;56:143–50.

[14] Micolucci F, Gottardo M, Cavinato C, Pavan P, Bolzonella D. Mesophilic and thermophilic anaerobic digestion of the liquid fraction of pressed biowaste for high energy yields recovery. Waste Manag 2016;48:227–35

[15] Colussi I, Cortesi A, Piccolo CD, Galloa V, Fernandeza ASR, Vitanza R. Improvement of methane yield from maize silage by a two-stage anaerobic process. Chem Eng Trans 2013;32:151–6.

[16] US Environmental Protection Agency (EPA). Biosolids technology fact sheet: Multi-stage anaerobic digestion. Report. Washington, DC: Office of Water, EPA; 2006 Sep

[17] Yabu H, Sakai C, Fujiwara T, Nishio N, Nakashimada Y. Thermophilic two-stage dry anaerobic digestion of model garbage with ammonia stripping. J Biosci Bioeng 2011;111(3):312–9

[18] Park Y, Hong F, Cheon J, Hidaka T, Tsuno H. Comparison of thermophilic anaerobic digestion characteristics between single-phase and two-phase systems for kitchen garbage treatment. J Biosci Bioeng 2008;105(1):48–54.

[19] Blonskaja V, Menert A, Vilu R. Use of two-stage anaerobic treatment for distillery waste. Adv Environ Res 2003;7(3):671–8.

[20] Kim J, Novak JT, Higgins MJ. Multi-staged anaerobic sludge digestion processes. J Environ Eng 2011;137(8):0000372.

[21] Nasr N, Elbeshbishy E, Hafez H, Nakhla G, El Naggar MH. Comparative assessment of single-stage and two-stage anaerobic digestion for the treatment of thin stillage. Bioresour Technol 2012;111:122–6

[22] Li Y, Park SY, Zhu J. Solid-state anaerobic digestion for methane production from organic waste. Renew Sustain Energy Rev 2011;15(1):821–6.

[23] Russo L, Ladisch M. Gaps in the research of 2nd generation transportation biofuels. Final report. Paris: IEA Bioenergy; 2008.

[24] Kacprzak, A., Krzystek, L., Ledakowicz, S., 2010. Co-digestion of agricultural and industrial wastes. Chem. Pap. 64(2), 127-131.

[25] Nielsen, L.H., Hjort-Gregersen, K., Thygesen, P., Christensen, J., 2002. Samfundsøkonomiske analyser af biogasf llesanlg. Fødevareøkonomisk Institut, Rapport, 136.

[26] Al Seadi, T., 2002. Quality management of AD residues from biogas production. Proc. IEA Bioenergy, Task 24 - Energy from Biological Conversion of Organic Waste.

[27] Hoornweg, D., Bhada-Tata, P., 2012. What a waste: a global review of solid waste management. World Bank.

[28] Claassen, P.A.M., Van Lier, J.B., Contreras, A.M.L., Van Niel, E.W.J., Sijtsma, L et al., 1999. Utilisation of biomass for the supply of energy carriers. Appl. Microbiol. Biotechnol. 52(6), 741-755.

[29] Hoornweg, D., Bhada-Tata, P., 2012. What a waste: a global review of solid waste management. World Bank.

[30] Taherzadeh, M., Karimi, K., 2008. Pretreatment of lignocellulosic wastes to improve ethanol and biogas production: a review. Int. J. Mol. Sci. 9(9), 1621-1651

[31] Aslanzadeh, S., 2014. Pretreatement of cellulosic waste and high rate biogas production. University of Borås, Borås, Sweden.

[32] Ylitervo, P., Akinbomia, J., Taherzadeha, M.J., 2013. Membrane bioreactors' potential for ethanol and biogas production: a review. Environ. Technol. 34(13-14), 1711-1723.

[33] Youngsukkasem, S., Chandolias, K., Taherzadeh, M.J., 2015. Rapid bio-methanation of syngas in a reverse membrane bioreactor: membrane encased microorganisms. Bioresour. Technol. 178, 334- 340.

[34] Youngsukkasem, S., Rakshit, S.K., Taherzadeh, M.J., 2012. Biogas production by encapsulated methane-producing bacteria. BioResources. 7(1), 56-65.

[35] Banerjee S, Mudliar S, Sen R, Giri B, Satpute D, Chakrabarti T, et al. Commercializing lignocellulosic bioethanol: Technology bottlenecks and possible remedies. Biofuels Bioprod Bioref 2010;4(1):77–93.

[36] Biyogaz Teknolojisi- Ahmet Karadağ Fen Fakültesi Kimya Bölümü

[37] Bayrakçeken, H. (1997). Biyogaz Üretim Sistemi Tasarımı ve Uygulaması. Afyon Kocatepe Üniversitesi, Afyon.

[38] Buğutekin, A. (2007). Atıklardan biyogaz üretiminin incelenmesi. Marmara Üniversitesi, İstanbul