Original Article

Investigating sustainable low-emission renewable biogas for power plant generation from anaerobic digestion of wastewater activated sludge process

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ABSTRACT

The growing demand for sustainable energy highlights the importance of biogas as a renewable and low-emission fuel. This study investigates the potential for biogas production from wastewater sludge via anaerobic digestion (AD) as a substitute for natural gas in power generation plants. A comparative analysis was conducted at the Al-Khums power plant located in Libya, focusing on efficiency and environmental impacts. The AD process was modeled through its four stages, namely: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The resulting upgraded biogas composition after purification was found to be 97.70% CH_4 and 2.30% CO_2. Process simulations using Aspen Plus v.12 evaluated the performance of biogas versus natural gas under varying loads. Key indicators, including thermal efficiency, specific fuel consumption, and CO_2/NO_x emissions, were compared. The electrical energy per cubic meter (m^3) was evaluated for natural gas and biogas fuels, in terms of MWh generated for a typical wastewater treatment plant. The electrical energy generated per cubic meter (m^3) from each fuel showed that biogas demonstrates significant environmental advantages, supporting its role in the sustainable energy transition.

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Introduction

The increase in global demand for clean energy, *e.g.,* electricity, and the limitation of CO_2 emissions are major problems and concerns facing the world today. This fact requires an increase in the amount of research work to establish a prompt solution. Similarly, electricity produced from traditional sources, such as fossil fuels, is a major source of greenhouse gas emissions [1-3]. Moreover, fossil fuels face imminent depletion, while countries that rely on oil imports face significant energy security challenges due to their reliance on fossil fuels, the supply of which is greatly affected by several external factors. Such factors recently have contributed to an increase in global interest in finding more sustainable alternative energy sources that will ensure a clean environment and future energy generation and supply [4].

Biofuel is the most important and reliable alternative source of energy in the future, and it can be produced from multiple renewable and inexhaustible sources [5,6]. Among these sources are the huge amounts of activated sludge sewage that are generated and released from wastewater treatment plant operations. The physical, chemical and biological characteristics of the generated sludge, and its huge quantities may pose a major threat to the environment in terms of management and disposal. For example, in America, China, and Europe, the annual production of sludge from treatment plants was estimated at 240 MT in 2010 [7]. These quantities have witnessed rapid growth over time. For example, in China, the growth rate reached approximately 13% from 2007 to 2013, with 6.25 MT of dry solids in 2013, only 25% of which was appropriately treated [8]. In 2017, the global sewage sludge production rate was approximately 45 dry MT per year [9-12]. In 2015, five European Union countries [the United Kingdom, Germany, Spain, France, and Italy] were reported to have domestic sewage sludge production that accounted for approximately 75% of the continent's total [13]. In the same year, the annual production of sewage sludge in China and Taiwan was recorded at approximately 30-40 MT and 77,000 MT, respectively [12,14]. In general, if these wastes are disposed of in traditional, direct ways, such as burial in the ground or sanitary landfilling, will pose a challenging risk to groundwater. Sanitary landfilling of generated sludge may cause the contents of waste sludge to decompose due to bacterial activities, resulting in byproducts such as methane gas, which is considered one of the most dangerous greenhouse gases due to its high global warming potential, when released into the atmosphere for long long-term persistence [15-18]. This contributes to the exacerbation of the climate change crisis due to methane's high activity, which is 25-28 times greater than that of carbon dioxide [19,20].

Anaerobic Digestion (AD) is one of the best methods for utilizing wastewater sewage sludge generated as a raw material for producing biogas through bacterial activities once the proper conditions are available for bacterial growth to cause the decomposition of sludge [21-24]. Furthermore, in addition to producing biogas, the digestion products can also be used as an agricultural fertilizers, because such products are rich in nitrogen and certain minerals [25-27]. In the AD process, methane, carbon dioxide, and small amounts of other gases are produced through the activities of several large groups of bacteria and archaea. Biogas is obtained through four basic steps [28-30], namely: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. In the first step, glucose, fatty acids, and amino acids are obtained by decomposing complex substances such as fats, proteins, and carbohydrates. In the second step, the hydrolyzed substances are converted into various volatile fatty acids, such as caproic acid, butyric acid, iso-butyric acid, propionic acid, valeric acid, iso-valeric acid, and acetic acid, as well as hydrogen and carbon dioxide. Finally, methane is obtained by methanogens, which convert the acetogenesis products into methane and carbon dioxide. Nonetheless, the mechanisms of these complex reactions in biogas production are very complicated and not well understood. There are several fundamental factors that directly affect the biogas production, including the organic loading rate (OLR), carbon-to-nitrogen (C/N) ratio, hydraulic retention time (HRT), ammonia concentration, pH, temperature, and mixing [31-33]. In addition to the series of bacterial metabolic reactions that occur during anaerobic digestion or fermentation, this makes their practical study extremely difficult and complex. However, with the help of some models, these factors, alongside the series of bacterial metabolic reactions involved in fermentation, can be well explained. In this context, several different mathematical models have emerged. The first mathematical model relied on acetate as the rate-limiting step, where only substrate inhibition was involved [34,35]. The BIOTREAT model, meanwhile, focused on explaining the series of intermediate reactions during fermentation based on electron donors and acceptors [36,37].

Complex inhibitors such as ammonia, the growth rate of microorganisms, pH, temperature, and the reactions involved affect biogas production. Ammonia formation depends on key parameters such as temperature and pH, which can be used to predict the amount of ammonia produced, which in turn affects biomethane formation. The interpretation of the inhibitors' effect on biogas production rate can be well investigated using the complex models developed by [38,39]. Recently, other complex models have been developed [40]. Although these models are widely used in the investigation of biogas production based on several basic parameters that greatly affect the biogas production process, other related complex models were used to investigate and interpret the impact other parameters on the process, such as the hydrolysis rate, thermal decomposition rate, and reaction thermodynamics**.** Therefore, most modern research focuses on the use of process simulation models due to their ability to accurately predict, analyze, and fully describe the real scenario in a shorter time and without high costs. Aspen Plus v.12 simulator is the most advanced program in this field due to its library functions that include inhibitors, intermediate reactions, and kinetics. In this research, the anaerobic digestion process simulation model (ADPSM) using Aspen Plus v.12 was used to simulate biogas synthesis reactors under thermophilic conditions (45 °C). The novelty of this work lies in the integrated approach combining ADPSM with gas turbine power plant simulation using local Libyan data (Al-Khums power plant), whereas previous studies [33] focused solely on the digestion process without downstream energy conversion. The effect of some basic parameters, such as temperature, HRT, pH, and C/N ratio, on the biogas production rate was also investigated. A sensitivity analysis to achieve optimal conditions was performed. The produced biogas was also used as a fuel to simulate a gas turbine-powered power plant. All findings and results of this research work were compared with the previous investigations and studies to verify and obtain satisfactory results, taking into consideration the impact of the most important bacterial growth factors.

Methods and Simulation

Anaerobic Digestion Model Simulation

Modeling and simulating any industrial process require a good knowledge of the natural conditions of the process, as well as familiarity with the simulation programs and the optimal selection of the mathematical models in the simulator used. The Aspen Plus v.12 simulator was utilized, and the three parameters of the NRTL (Non-Random-Two-Liquid) equation were chosen to obtain accurate thermodynamic results. Mass and energy balance balances were performed based on real data according to[33, 41] on each piece of equipment in the process, to determine the biogas production rate as well as associated conditions during the process and consequently establish an improved process. To control the AD process and its accompanying changes, it is necessary to study the state of incoming and outgoing compound flows as well as the series of reaction kinetics involved. The main objective of modeling is to describe the behavior of the AD process correctly and realistically. Therefore, simulating the AD process, which is based on a series of basic reactions, depends mainly on the flow rates and composition of the feedstock, in addition to the appropriate conditions inside the reactor that directly affect the biogas production rate.

Process Configuration and Operational Description

Figure 1 presents a simulation flow of the AD process. First, 4039.52 kg/s of methyl diethanolamine (MDEA) solution is pumped and heated to 60 °C before entering the absorption column to improve its effectiveness in the subsequent absorption step. In contrast, a sludge stream of 190 kg/s enters the Stoichiometric Reactor (SR) as a feedstock at an initial temperature of 20°C and a pressure of 1 atm. This step is crucial as it simulates the initial stage of anaerobic digestion, *i.e.,* the hydrolysis stage, where the complex organic compounds such as carbohydrates, proteins, and lipids are broken down into simpler, soluble molecules like sugars, amino acids, and fatty acids. The exit stream (S1) at 55 °C and 1 atm enters the main digestion reactor (MDR). This step represents the core biological digestion stages, *i.e.,* acidogenesis, acetogenesis, and methanogenesis, which occur concurrently. In the acidogenesis stage, the products from stage 1 are further broken down into volatile fatty acids, alcohols, hydrogen, and carbon dioxide. These are then converted into acetic acid, CO_2, and H_2 in the acetogenesis stage. Finally, methanogenic microorganisms convert acetic acid and hydrogen in the final stage into methane (CH_4) and carbon dioxide (CO_2). The two streams exit from the MDR at 55 °C and 1 atm. The undesired liquid stream is disposed of from the bottom as a side stream. The gas phase, or desired stream, contains mainly methane and other gaseous by-products. This stream enters the cooler after being compressed to 6.5 atm by the compressor. The temperature of the compressed gas is cooled from 104.7 to 60 °C to achieve optimal conditions for the next step in the absorption column. The cooled biogas stream (at 60 °C and 6.5 atm) enters the Absorber, where it interacts with the MDEA solution. The purpose of this absorption step is to remove impurities such as carbon dioxide, resulting in a purified biogas product. A high-quality biogas stream exits at 69.8 °C and 7.96 atm. This stream has a lower impurity content, making it suitable for energy applications. A secondary stream exits from the bottom at 70.37 °C and 8.9 atm, which contains the removed impurities and other by-products.

Main Biochemical Reactions

Anaerobic digestion consists of a series of biochemical reactions where bacteria break down the organic matter of any substrate into a gaseous mixture (CH_4, CO_2, H_2, H_2S, etc.) in the absence of free oxygen. Some groups of bacteria involved in the digestion process cannot survive in the presence of oxygen. Therefore, an anaerobic (oxygen-free) environment is necessary for the process. The AD process typically occurs in a closed vessel.

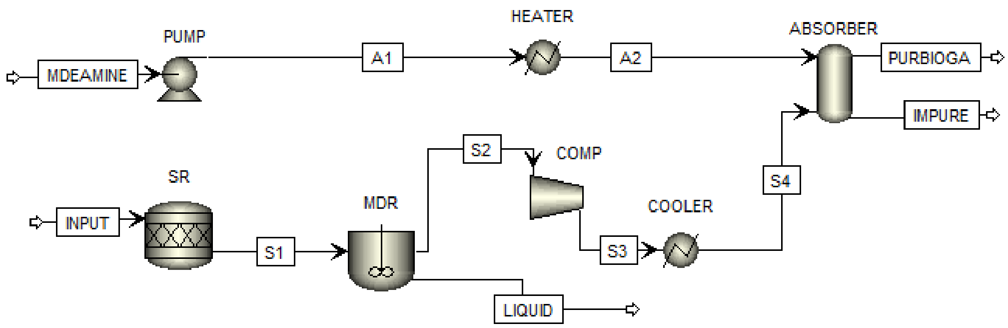


Figure 1: A schematic diagram of ADPSM used in this study

Produced biogas flows out to temporary storage and later on to the end-use applications. The main coandmmercial applications of biogas are heat and electricity generation. After AD, the vessel will contain residual solids and organic matter known as digestate. Digestate can be separated into liquid and solid streams. Both streams contain valuable plant nutrients and can serve as a fertilizer in agricultural applications. The AD process occurs through several complex steps, driven by interactions between different groups of microorganisms. These microbial communities decompose the biomass in the absence of oxygen through a series of digestion reactions, converting it into a gaseous mixture containing primarily methane, carbon dioxide, and digestate. This complex series of biochemical reactions can be divided into four main stages: i) hydrolysis, ii) acidogenesis, iii) acetogenesis, and iv) methanogenesis. These main stages are discussed in detail in the following sections.

Hydrolysis Reactions

The hydrolysis stage is one of the essential initial stages required for biogas synthesis. It occurs at a temperature of 20 °C and a pressure of 1 atm inside the SR reactor, as displayed in Figure 1. During this stage, the complex polymeric structures of the compounds entering the reactor are broken down into simpler units by water and enzymes. Cellulose, starch, and proteins are broken down into glucose, fatty acids, and amino acids. These compounds are then ready to be converted into biogas. However, despite the rapid growth of bacteria at this stage, they require further decomposition in the subsequent stages. A series of hydrolysis reactions is indicated in Table 1 [33].

Acidogenic Reactions

This stage occurs immediately after hydrolysis in the MDR reactor shown in Figure 1. This process occurs rapidly under certain conditions, such as 55 °C and 1 atmosphere. Acidophilic bacteria further decompose the hydrolysis products from the SR reactor. These products are converted into short-chain volatile fatty acids, alcohols, and ketones, as well as carbon dioxide, hydrogen, ammonia, and other byproducts. Some of these products can be directly converted to biomethane via methanogens, while others require further decomposition. Table 1 presents the main reactions in this stage [33].

Acetogenic Reactions

Acetogenic bacteria convert the products of the previous step into acetate, carbon dioxide, and hydrogen through acetogenic reactions. These reactions are non-spontaneous if the partial pressure of hydrogen is above the range of 4-10 atm.

Table 1: List of hydrolysis, acidogenic, acetogenic, and methanogenic reactions

No.	Chemical reactions
	Hydrolysis reaction
1	$(C_6H_{12}O_6)_n + H_2O \rightarrow n\ C_6H_{12}O_6$
2	$(C_6H_{12}O_6)_n + H_2O \rightarrow n\ C_6H_{12}O_6$
3	$C_5H_8O_4 + H_2O \rightarrow C_2H_4O_2$
4	$C_5H_8O_4 + H_2O \rightarrow C_5H_{10}O_5$
5	$C_5H_{10}O_5 \rightarrow C_5H_4O_2 + H_2O$
6	$C_6H_{12}O_6 + H_2O \rightarrow C_2H_6O + CO_2$
7	$C_{13}H_{25}O_7N_3S + H_2O \rightarrow CO_2 + CH_4 + H_3N + H_2S$
8	$I.P + H_2O \rightarrow C_6H_{14}N_4O_2 + C_4H_7NO_4 + C_4H_9NO_3 + C_3H_7NO_3 + C_5H_9NO_4 + C_5H_9NO_2 + C_2H_5NO_2 + C_3H_7NO_2 + C_3H_6NO_2S + C_5H_{11}NO_2 + C_6H_{13}NO_2 + C_6H_{13}NO_2 + C_9H_{11}NO_2$
9	$C_{57}H_{104}O_6 + 3\ H_2O \rightarrow C_3H_8O_3 + C_{18}H_{34}O_2$
10	$C_{51}H_{98}O_6 + H_2O \rightarrow C_3H_8O_3 + C_{16}H_{34}O$
11	$C_{37}H_{70}O_5 + H_2O \rightarrow C_3H_8O_3 + C_{16}H_{34}O + C_{18}H_{34}O_2$
12	$C_{37}H_{68}O_5 + H_2O \rightarrow C_3H_8O_3 + C_{16}H_{34}O + C_{18}H_{32}O_2$
	Acidogenic Reactions
13	$C_6H_{12}O_6 + H_3N \rightarrow C_5H_7NO_2 + C_2H_4O_2 + C_3H_6O_2 + C_4H_8O_2 + CO_2 + H_2O$
14	$C_3H_8O_3 + H_3N + CO_2 + H_2 \rightarrow C_5H_7NO_2 + C_3H_6O_2 + H_2O$
	Acetogenic Reactions
15	$C_{18}H_{34}O_2 + H_2O + CO_2 + H_3N \rightarrow C_5H_7NO_2 + C_2H_4O_2 + H_2$
16	$C_3H_6O_2 + H_3N + H_2O \rightarrow C_5H_7NO_2 + C_2H_4O_2 + CH_4 + CO_2 + H_2$
17	$C_{18}H_{32}O_2 + H_2O + CO_2 + H_3N \rightarrow C_5H_7NO_2 + C_2H_4O_2 + H_2$
18	$C_{16}H_{34}O + H_2O + CO_2 + H_3N \rightarrow C_5H_7NO_2 + C_2H_4O_2 + H_2$
	Methanogenic Reactions
19	$C_2H_4O_2 + H_3N \rightarrow C_5H_7NO_2 + CH_4 + H_2O + CO_2$
20	$H_2 + CO_2 + H_3N \rightarrow C_5H_7NO_2 + CH_4 + H_2O$

However, this partial pressure gradually decreases due to the presence of methanogenic bacterial populations. Some of the producing bacteria are fed on other bacterial products, making acetate formation thermodynamically feasible. At this stage, hydrogen proton transfer is very important for the digestion reactions. Equations 15 through 18 illustrate the main reactions in this stage, as shown in Table 1 [33].

Methanogenic Reactions

This stage represents the final step in biomethane synthesis. It builds on the results of previous intermediate stages. Essentially, this stage relies on two types of bacterial groups: an acetophilic group that converts acetate into biomethane and carbon dioxide, while the other group, hydrogenophilic, converts hydrogen and carbon dioxide into biomethane. Equations 19 and 20 represent the main reactions in this stage, as indicated in Table 1 [33].

Feed Stock Input

Biogas production depends primarily on the type of biomass and concentration used in the production process. In general, all organic materials can be digested according to the specific operating conditions. Table 2 shows the composition of the feedstock used in this study for biogas synthesis [33,41]. It contains a high moisture content of approximately 35%, in addition to some basic components such as cellulose and hemicellulose, each accounting for approximately 20%. Other components range from 0.2 to 10%.

Utilization of Biogas in Electricity Generation

Biogas has long been used as a fuel for direct combustion for various purposes, including cooking, lighting, and more. Now, with the rapid development of biogas synthesis processes producing biogas with high thermal quality and specifications, it is increasingly being used to generate other types of energy, *e.g.,* electricity, in many countries.

Biogas-fired power generation using turbines and fuel cells has proven commercially viable, despite ongoing research to improve efficiency and performance [42]. Most recent research conducted in this context in developing countries in Africa and industrialized countries such as Germany has shown that this method is not economically viable when applied to small plants. Therefore, biogas-fired power plants, especially small ones, require financial and technical support to encourage investors in this field. To achieve sustainability in biogas-based power generation, the turbine engines used in generation must have higher conversion efficiency, be easy to operate and maintain, and have a low investment cost to produce competitively priced electricity.

Biogas to Electricity Conversion Model Simulation

The simulation model was developed using Aspen Plus v.12 simulator based on Al-Khums power station data, as previously mentioned in [43]. The electricity generation plant was simulated using both natural gas (the current fuel used to operate the plant) and biogas (produced in this study) as fuel sources. The plant was operated at five different power capacities: 150, 165, 185, 220, and 240 MW, respectively. At each power level, the following parameters were recorded: (1) CO_2 and NO_x produced per unit of electricity, (2) thermal efficiency, (3) emissions, specifically CO_2 and NO_x levels, and (4) fuel consumption rate. The results obtained are discussed in detail in Section 4.

Table 2: Feedstock input

Component	Value (kg/kg)
Cellulose ($C_6H_{10}O_5$)	0.2
Dextrose ($C_6H_{12}O_6$)	0.1
Hemicellulose ($C_5H_8O_4$)	0.2
Keratin	0.03
Protein	0.08
1-Palmitoyl-2-linoleoyl-sn-glycerol ($C_{37}H_{68}O_5$)	0.01
Triolein ($C_{57}H_{104}O_6$)	0.01
Tripalmitin ($C_{51}H_{98}O_6$)	0.01
NH_3	0.002
Inert	0.008
Water	0.35

Results and Discussion

Biogas Production

As a result of simulating the AD process followed by MDEA absorption purification, the composition and specifications of the produced upgraded biogas are listed in Table 3. The raw biogas composition before purification was 58.1% CH_4, 35.9% CO_2, 0.99% H_2S, and traces of other gases, consistent with the literature ranges.

Main Parameters Affecting Biogas Production

Anaerobic digestion occurs through several complex stages, and the bacteria involved are influenced by the parameters of these stages. Some of these parameters include temperature, hydraulic retention time (HRT), acidity (pH), organic loading rate (OLR), and carbon-to-nitrogen ratio (C/N), as depicted in Figure 2.

Table 3: Composition and specifications of the purified produced biogas

Compound	MW = 16.8; Density = 0.749 kg/m^3 (at STP); LHV = 49034 kJ/kg		
	Formula	**Unit**	**Value**
Methane	CH_4	mol. %	97.7
Carbon dioxide	CO_2	mol. %	2.3
Total	--	--	100

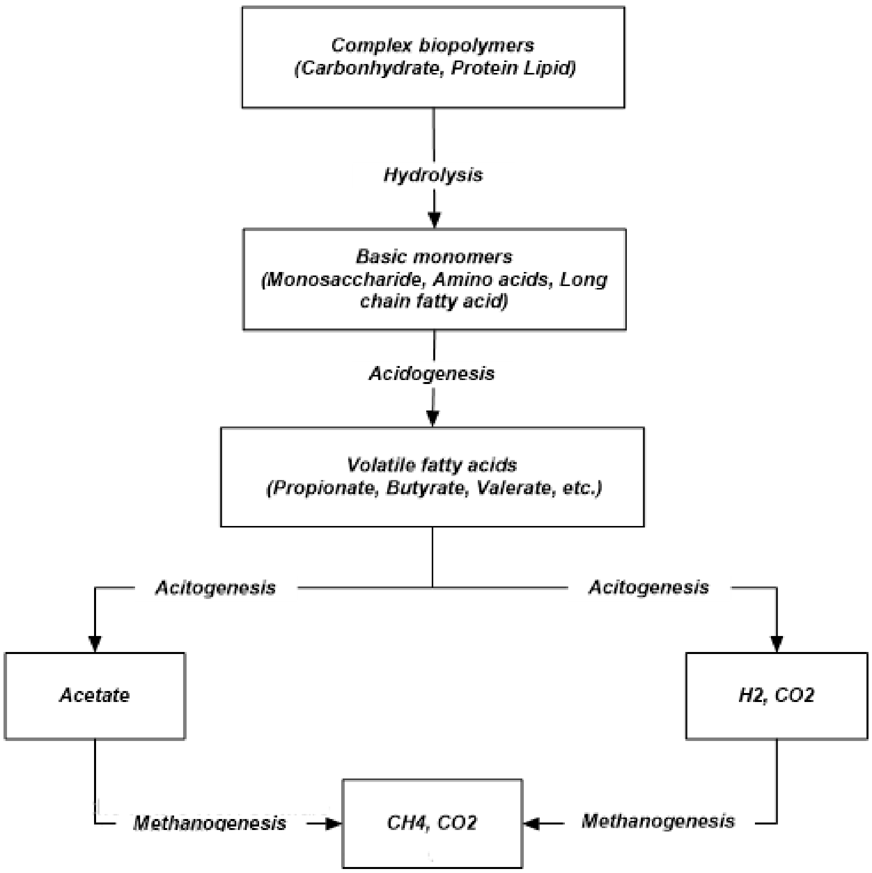


Figure 2: A schematic representation of hydrolysis, acidogenesis, acetogenesis, and methanogenesis in organic matter degradation

Based on the feedstock properties and the surrounding environment, optimizing these parameters controls the efficiency and speed of the digestion process, among other factors. Furthermore, the composition and properties of the raw material, along with the surrounding environmental conditions can greatly impact the efficiency and speed of the digestion process when process optimization is required. The following sections discuss in detail the impact of the most prominent of these parameters on biogas production.

Temperature

Temperature is one of the most important factors affecting the efficiency of biogas production through the anaerobic digestion process. In general, anaerobic digestion can occur in several different temperature ranges: 10-25, 30-42, and 48-65 °C, which are classified as psychrophilic, mesophilic, and thermophilic, respectively. Processes occurring in psychrophilic and mesophilic ranges are considered relatively simple and economical in terms of construction and operation because they do not require heat exchange units. However, their disadvantages include requiring a long time and a large digestion volume compared to the thermophilic digestion process. Accordingly, in this study, the biogas production rate was simulated and tested over different temperature ranges. Figure 3 demonstrates the effect of different temperature ranges on the biogas yield.

Based on Figure 3, it is observed that thermophilic digestion can produce a higher biogas production rate, estimated to be more than 50% higher than mesophilic digestion. This is due to the higher digestion rate resulting from the greater availability of microbes, especially those capable of degrading fat-containing substrates [44,45]. Furthermore, high temperatures significantly contribute to the killing of harmful pathogenic bacteria, which makes it safer and more environmentally friendly. Although the disadvantages of this process include difficulties in initial operation and achieving optimal conditions for microbial growth, a temperature of 55 °C is considered optimal for achieving maximum performance of anaerobic bacteria.

Hydraulic Retention Time HRT

Hydraulic retention time (HRT) is defined as the number of days the substrate must remain within the digester for maximum conversion of organic matter to biogas. However, longer retention times typically require a larger digester, which increases cost, and also have disadvantages such as operational complexity and difficulty controlling some key parameters, such as temperature. Therefore, the time required for microbial growth and substrate conversion to biogas depends primarily on several key factors, including operating conditions, substrate type, and especially temperature, as discussed in the previous section.

Figure 4 illustrates the effect of HRT on the biogas production rate. The relationship between HRT and biogas production rate is directly proportional. The longer the number of days represented by HRT, the greater the microbial growth and, consequently, the higher the substrate conversion rate to biogas. Therefore, the optimal time period for achieving the highest conversion rate is 45 days.

pH

The medium pH is one of the essential parameters that influence the efficiency of the AD process. In general, although most microorganisms prefer a neutral pH range, an optimal pH range is required for each stage of the process to achieve maximum possible performance, as shown in Figure 5.

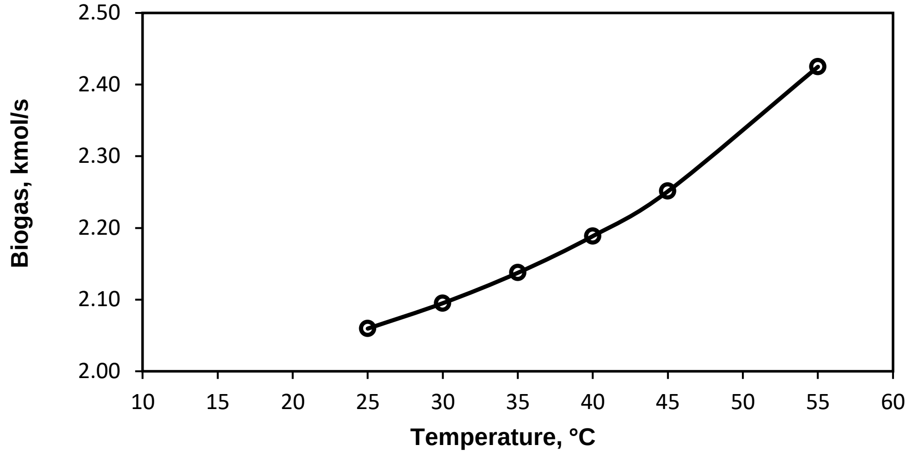


Figure 3: Effect of temperature on biogas production

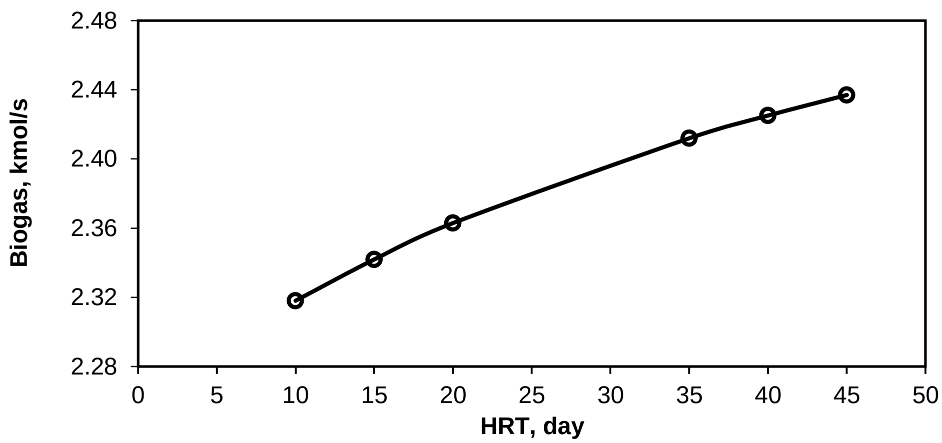


Figure 4: Effect of HRT on biogas production

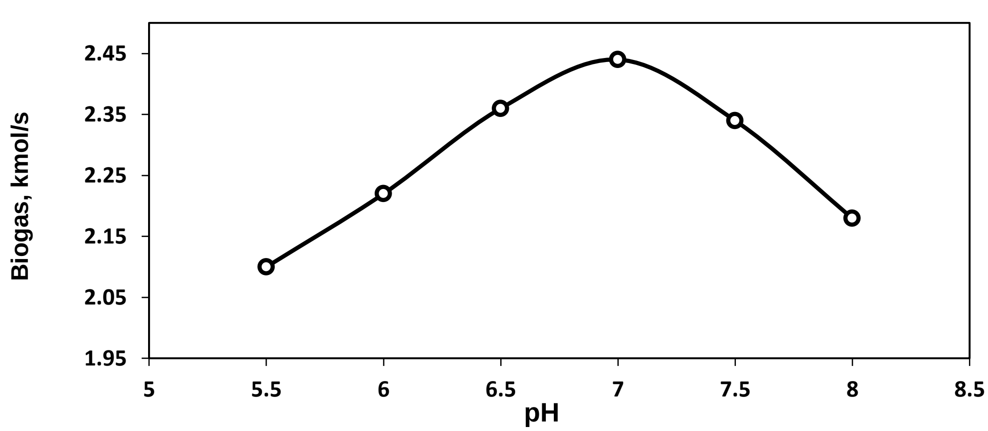


Figure 5: Effect of pH on biogas production

Thus, for methanogens, a pH of 7 is preferred, while hydrolytic and acidogenic bacteria perform best in the pH range of 5.5 to 6.5. Maintaining the required pH ranges at each stage is a major challenge, especially in sensitive stages of processes that contain substrates with different compositions, such as sewage sludge.

Carbon/Nitrogen (C/N) Ratio

Another crucial factor in the AD process is the C/N ratio in the substrate. Most AD processes prefer a ratio of 20 to 30, depending on the type and properties of the substrate [46]. A low carbon content in the substrate leads to excess ammonia production and increased alkalinity in the digester, which hinders the overall process and reduces biogas production. Conversely, a low nitrogen content in the substrate negatively impacts protein synthesis, as microorganisms consume almost all the available nitrogen, leaving insufficient nitrogen for their own metabolism. This behavior can be clearly observed in Figure 6.

Electricity Generation Analysis and Impacts

The performance and effectiveness of biogas in generating electricity were verified by comparing the results obtained through the simulation process referred to in Section III. The station was simulated using two types of gaseous fuels: (1) upgraded biogas and (2) natural gas. The simulation results show that, at each power level, the performance of natural gas differs slightly from that of biogas. This is attributed to several important factors, *e.g.,* the gas composition, *i.e.,* carbon content and its calorific value, which is higher in the case of upgraded biogas than that of natural gas, as illustrated in Figure 7.

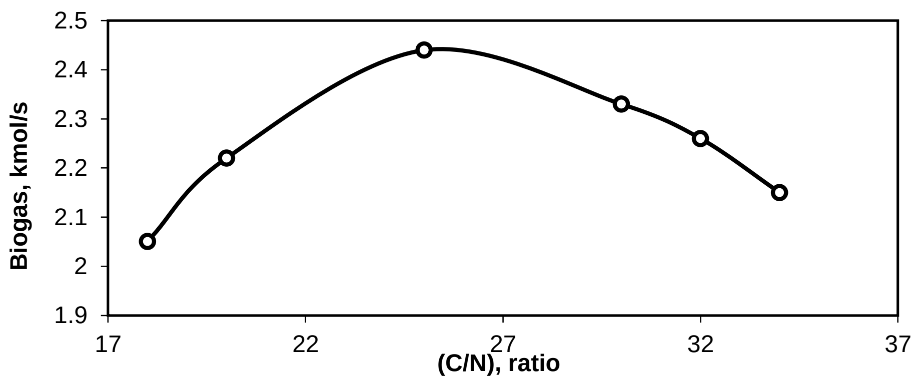


Figure 6: Effect of C/N ratio on biogas production

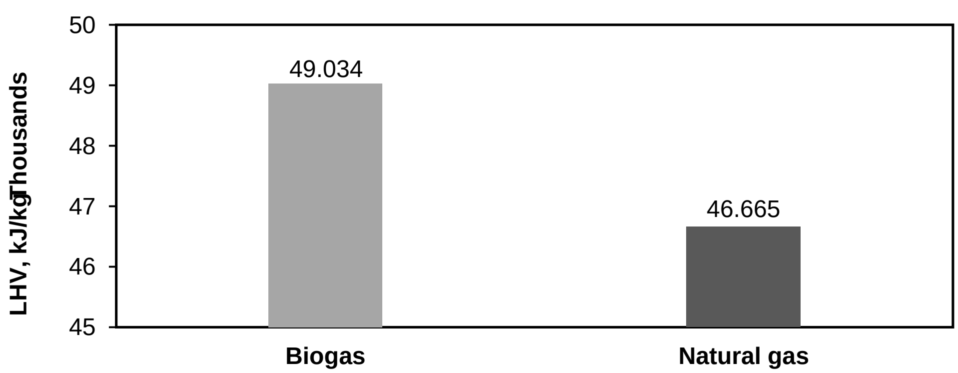


Figure 7: Lower Heating Value (LHV) on mass basis (std) [kJ/kg]

Consequently, the required feed rate of upgraded biogas to generate the same electrical energy is 0.9516 times that of natural gas (Figure 8 presents the mass flow rates of both gaseous fuels at various electrical loads). Natural gas exhibits a higher mass flow rate than upgraded biogas at the same power output, indicating that natural gas has a lower calorific value per unit mass. Conversely, the lower flow rate of upgraded biogas enhances its attractiveness from environmental and economic perspectives. The impact of fuel rate entering the combustion chamber on the NO_x and CO_2 emissions per kilo-watt has been well investigated. Figure 9 illustrates the resulting emission rates at different capacities. In addition to emission analysis, the thermal efficiency of the power plant was evaluated at five different electrical loads (150, 165, 185, 220, and 240 MW) for both natural gas and upgraded biogas. Table 4 presents the comparison of thermal efficiency under each operating condition.

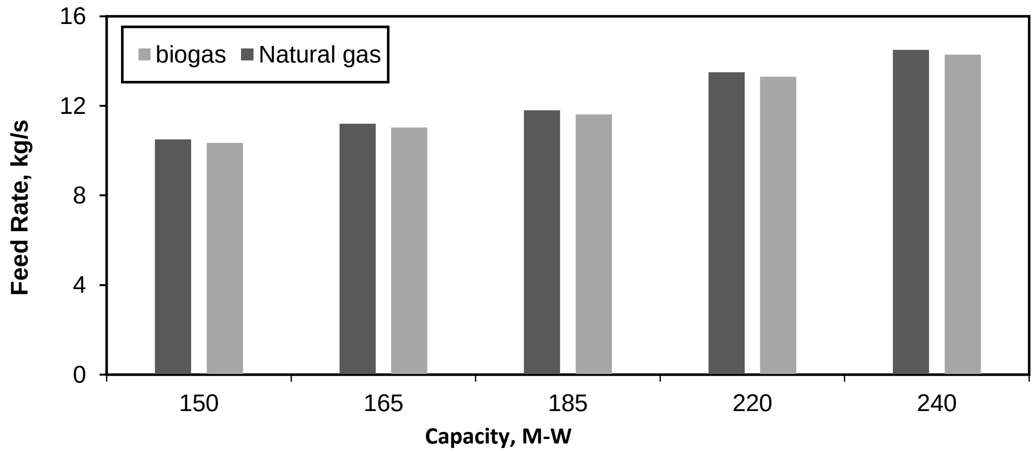
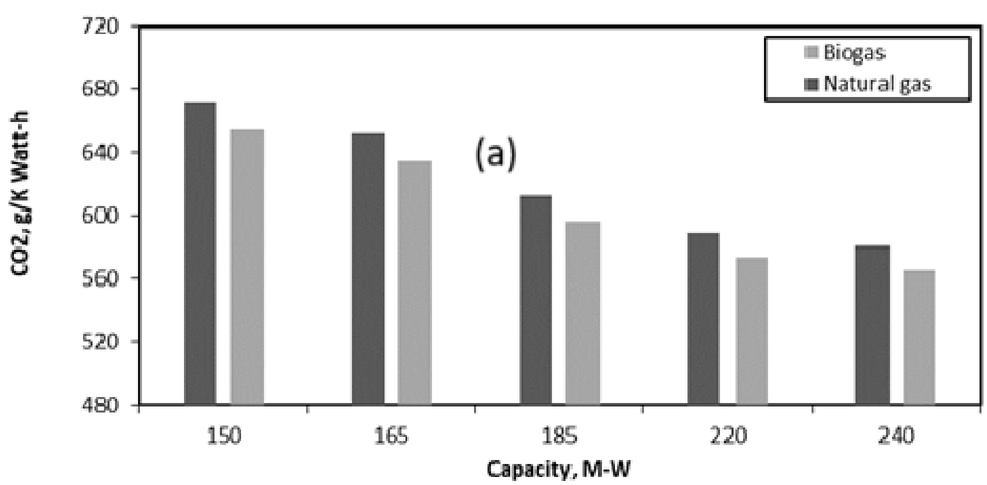


Figure 8: Electric power vs. mass feed rate



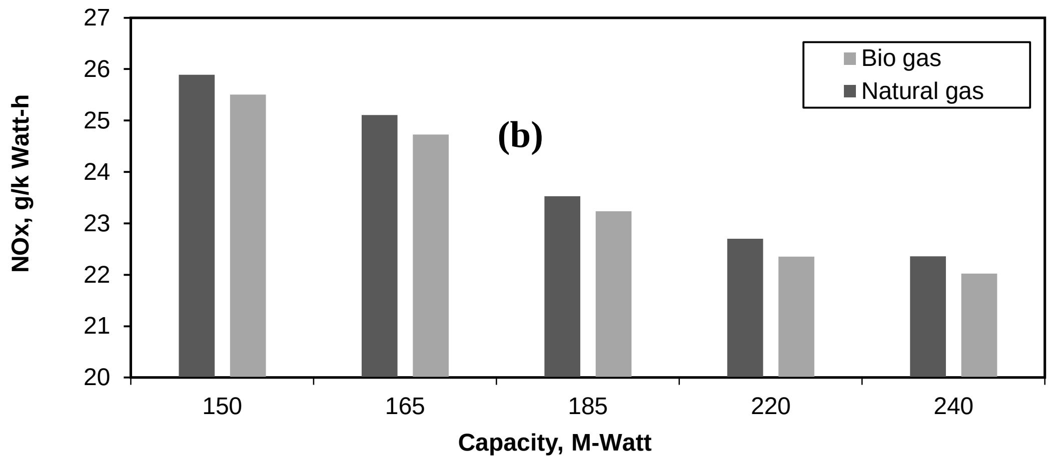


Figure 9: (a)Impact of fuel consumption rate on CO_2 emission rate at different capacities (b) Impact of fuel consumption rate on NO_x emission rate at different capacities

Table 4: Comparison of power plant thermal efficiency using natural gas vs. upgraded biogas at different electrical loads

Power (M- W)	Efficiency (%)	
	Natural gas	Upgraded biogas
240	35.465	35.466
220	34.918	34.919
185	33.593	33.594
165	31.567	31.567
150	30.610	30.611

The results in Table 4 demonstrate that the thermal efficiency of upgraded biogas is nearly identical to that of natural gas across all load conditions, with a negligible difference of approximately 0.001–0.003%. This confirms that after purification (97.7% CH_4), biogas can directly substitute natural gas in gas turbines without compromising thermal performance. The slight advantage observed at higher loads (*e.g.,* 240 MW) is within simulation tolerance, but overall, the efficiency values are virtually equivalent, validating the technical feasibility of biogas as a drop-in replacement fuel.

Generally, using biofuels to produce electricity results in lower emission rates than natural gas as a fuel. This can be explained by the low carbon content and high heating value of biogas. Although biogas has a relatively lower environmental impact than natural gas, its use is still associated with greenhouse gas emissions, particularly CO_2 and NO_x. The impact depends on the technology for producing biogas and converting it into electrical energy. This means that the environmental impact of biogas used for energy production depends largely on the biogas production technologies and the technologies used to convert it into useful energy. Although the use of biogas in electricity generation is relatively high in developed countries, it is not widely used in developing countries despite the availability of raw materials, *i.e.,* biomass, for its production. A comparison between natural gas and biogas produced from anaerobic wastewater sludge is detailed in Table 5, which captures the main technical parameters: composition, energy values, impurities, efficiencies, emissions, economics, and application scope [47-49].

Table 5: Comparison table of natural gas vs. sewage-sludge biogas

Parameter	Natural gas (fossil fuel)	Biogas from anaerobic digestion of sludge
Primary composition	CH_4 ~ 85–98%; small amounts of C_2–C_6, N_2, CO_2	CH_4 ~ 45–75%; CO_2 ~ 25–55%; traces H_2S, siloxanes, NH_3, moisture
Lower Heating Value (LHV)	34–52 MJ/m^3 (typical pipeline gas, regional variation)	18–26 MJ/m^3 (depends on CH_4 %)
Higher Heating Value (HHV)	~38–55 MJ/m^3	~20–28 MJ/m^3
Methane number (engine knock resistance)	High (> 80–90, very stable for engines)	Variable (50–80), depends on CO_2 dilution and impurities
Typical impurities	Minimal (pipeline standard)	H_2S, siloxanes, moisture, and particulates
Gas quality stability	Very stable (regulated pipeline specification)	Variable; requires monitoring and pre-treatment.
Fuel processing required	None (ready-to-use)	Cleaning: H_2S removal, drying, siloxane removal; upgrading (if RNG for turbines/grid injection)
Energy density (per unit volume)	High, ~ 35–50 MJ/m^3	Lower, ~ 18–26 MJ/m^3
Power plant compatibility	Gas turbines (simple/combined cycle), reciprocating engines, micro turbines, fuel cells	Reciprocating gas engines (best), micro turbines; turbines only with upgraded RNG; fuel cells need deep cleaning
Typical electrical efficiency	50–62% (large NGCC); 35–42% (reciprocating engines)	30–42% (reciprocating engines with CHP); 20–30% (micro turbines on raw biogas)
CHP potential	yes; large-scale combined heat and power	Excellent for WWTPs (heat used for Digester heating and plant needs)
Lifecycle GHG emissions	330–500 gCO_2 e/kWh (depends on efficiency & methane leakage)	Often near-zero or negative when considering avoided sludge methane release; combustion CO_2 treated as biogenic
Local pollutant emissions	Low SO_x, low particulates; NO_x present	Higher risk of corrosive/abrasive emissions ($H_2S \rightarrow SO_2$, siloxane → silica deposits)
Supply scale	Large, continuous, dispatchable from grid	Limited to sludge volume; steady but small scale (kW–MW at WWTP)
Fuel storage/transport	Pipeline networks, LNG for storage	Usually produced and consumed on-site; upgrading required for injection
Maintenance needs	Lower (clean fuel, less fouling)	higher (siloxane deposits, H_2S corrosion, more frequent oil/engine service)
Economic considerations	Fuel cost depends on market; stable technology, lower O&M	Fuel is "free" (waste-derived), but CAPEX/O&M for digesters, cleaning systems, and higher engine. maintenance
Environmental benefits	Cleaner than coal/oil, but still fossil CO_2	Renewable, reduces sludge disposal burden, captures methane, contributes to circular economy

Best application	Large-scale central power plants, baseload & peaking	On-site CHP at wastewater treatment plants, small/medium decentralized power

Limitations of the Study

This study has several limitations that should be acknowledged. First, the simulation assumes steady-state conditions and ideal mixing, which may not fully capture the transient behavior and spatial heterogeneity of real anaerobic digesters. Second, the kinetic parameters and microbial growth models were adopted from the literature [33] without experimental validation using site-specific sludge from Al-Khums. Third, the economic analysis is preliminary and does not include capital costs, maintenance, or operator training. Fourth, the study focuses on a single plant capacity range (150–240 MW) and does not explore smaller decentralized applications where biogas might be more competitive. Fifth, the environmental impact assessment does not include fugitive methane emissions from the digester or upgrading units. Future work should address these limitations through pilot-scale validation, techno-economic analysis, and life-cycle assessment.

Conclusion

Both natural gas and biogas are crucial for power generation; yet, they present distinct trade-offs between efficiency, reliability, and environmental impact. Natural gas offers high efficiency and operational stability, making it ideal for large-scale power generation through Natural Gas Combined Cycle (NGCC) plants; however, as a fossil fuel, it contributes significantly to CO_2 emissions. In contrast, biogas, derived from sources like wastewater sludge, is a carbon-neutral fuel that supports renewable energy generation and a circular economy. Although it has a lower energy density and requires purification, its utilization in Combined Heat and Power (CHP) systems at facilities such as wastewater treatment plants (WWTPs) is ideal, ensuring energy self-sufficiency, sustainable waste management, and total efficiency of up to 70–80%. A medium-sized WWTP can generate 3–4 GWh/year of renewable electricity from biogas, substantially reducing greenhouse gas emissions. Therefore, a hybrid approach is recommended: leveraging natural gas for its large-scale stability while integrating biogas for its low-carbon benefits. With advancements in purification and combustion technology, biogas is poised to be a key player in the global transition to a more sustainable and diversified energy mix. This hybrid strategy is best realised through a set of complementary measures: optimising biogas processing to reduce CO_2 content and thereby enhance its calorific value and efficiency; installing advanced combustion control systems to curtail NO_x emissions when using biogas; deploying hybrid systems that blend natural gas and biogas to balance operational performance with environmental gains, ensuring optimal output while minimising emissions; encouraging policy frameworks that promote biogas adoption via subsidies or carbon credits to offset its operational limitations; and, crucially, engineering enhanced combustion chambers with modified burner configurations and improved air-fuel mixing ratios to accommodate the inherent variability in biogas composition, with a focus on developing chambers that operate efficiently across different methane concentrations, thus improving combustion stability and further reducing emissions.

Recommendations

1) Optimization of Biogas Systems: Improve biogas processing to reduce CO_2 content, which would enhance its calorific value and efficiency.
2) Combustion Control Systems: Install systems to reduce NO_x emissions when using biogas as a fuel source.
3) Hybrid Systems: Use a blend of natural gas and biogas to balance efficiency and

environmental benefits, ensuring optimal performance while minimizing emissions.

4) Policy Support: Encourage policies that promote biogas usage through subsidies or carbon credits to offset its operational limitations and promote sustainable energy solutions.

5) Engineering of Enhanced Combustion Chambers: The design of combustion chambers should be optimized for biogas combustion. This includes modifying burner configurations and air-fuel mixing ratios to better handle the variability in biogas composition. Engineering efforts should focus on developing chambers capable of operating efficiently with biogas at different methane concentrations, thus improving combustion stability and reducing emissions.

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Graphical Abstract