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Process Optimization and Sustainability Assessment of Conventional Natural Gas and Bio Gas Production Process

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Abstract

The increasing global energy demand and environmental challenges have necessitated a critical evaluation of conventional natural gas and biogas production processes. This study focused on optimizing and assessing the sustainability of these processes using a set of defined Sustainability Indicators. By embedding sustainability principles into process design, the goal was to reduce resource consumption, emissions, and environmental impact, while maximizing economic and social benefits. A taxonomic classification of sustainability indicators, based on environmental and efficiency criteria, was proposed to allow for a more robust assessment of process sustainability. Additionally, a general sustainability scale was developed using best- and worst-case scenarios as benchmarks. The findings offer key insights into the sustainability performance of both energy sources, guiding stakeholders towards more eco-friendly and economically viable solutions. Quantitative and qualitative analysis revealed that biogas production is more efficient and environmentally sustainable compared to conventional natural gas production processes.

Keywords: Process Optimization, Sustainability Assessment, Environmental Impact, Resource Efficiency, Process Modeling.

1. Introduction

Bangladesh boasts abundant natural riches across its 147,610 square kilometers, spanning 600 kilometers east to west [1]. Bangladesh's natural gas is renowned for its exceptional purity, boasting methane levels between 95% to 99% and minimal sulfur content, making it a prized resource [2]. It emits fewer pollutants compared to oil and coal, and releases less carbon dioxide per energy unit [3]. Bangladesh ranks nineteenth in natural gas production across Asia, meeting 56% of its energy needs with local resources. Out of 27 gas fields, only two are located offshore [1].

In Bangladesh, Petro Bangla and Bangladesh Petroleum Corporation, the country's state-owned gas enterprises, oversee everything from gas production to distribution and exploration. They collaborate with international giants like Chevron, ConocoPhillips, and more for exploration and production endeavors. Notably, Chevron alone contributes half of the nation's natural gas output [4]. The natural gas consuming sectors in Bangladesh are: i) Power, ii) Fertilizer, iii) Industry, iv) Captive power, v) Domestic, vi) Commercial, and vii) Transportation (CNG). The usage of gas by fertilizer, industry, and captive power sectors is a substantial part of the nation's overall gas consumption [5]. Bangladesh stands out amidst the global landscape, with its unique reliance primarily on natural gas to fuel its commercial energy demands.

Bangladesh is now facing a critical challenge due to dwindling natural gas reserves and rising energy demands, raising concerns about the sustainability of natural gas as a primary energy source. With domestic consumption at 3,126 million cubic feet per day, of which 2,284 million is locally sourced, the nation risks depleting its reserves within the next decade. This shortage is further exacerbated by the lack of major gas field discoveries in the past 20 years, necessitating imports from the Middle East to bridge the gap. [6].

In the latter half of 2016, natural gas supply began a gradual decline, which accelerated as demand increased. The situation became critical when government-imposed restrictions limited supply to industries, power plants, and households, highlighting the growing energy challenge.

By 2022, natural gas contributed only 55% to power generation, leading the government to initiate costly liquefied natural gas (LNG) imports starting in late 2018. Rising energy costs have pressured consumers, intensifying the need for sustainable alternatives like biogas to address future fuel demands and ensure energy security.

2. Methodology

2.1. Process Specification of natural gas & bio gas

Maintaining gas quality is crucial for efficient natural gas transportation, requiring the removal of impurities and natural gas liquids through processing before entering high-pressure pipelines **(Fig. 1)**. This ensures compliance with standards for specific gravity, pressure, Btu content, and water content, preventing operational issues. Processing techniques, including hydrocarbon blending, are tailored to the raw gas composition and geological conditions at field or treatment plants. [7].

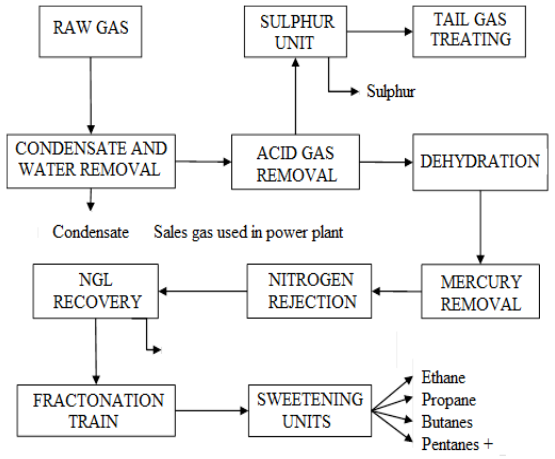


Fig. 1. Process flow of natural gas production [8]

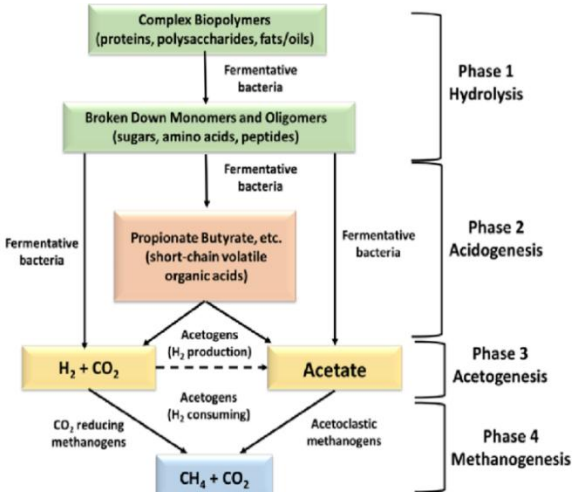


Fig. 2. Process flow of bio gas production process

Animal manure, such as cow dung, is utilized as feedstock for biogas production due to its substantial organic content. In the anaerobic digestion (AD) process from **Fig. 2**, microorganisms decompose this waste in an oxygen-free environment, generating biogas primarily composed of methane (CH_4) and carbon dioxide (CO_2), along with trace gases such as hydrogen sulfide (H_2S). The digestate remaining post-digestion is nutrient-rich and functions as an effective soil amendment. Upgrading biogas through CO_2 and H_2S removal yields biomethane, a high-quality renewable energy source.

The efficacy of biogas production is contingent upon maintaining optimal conditions within the digester throughout the AD process, which encompasses four sequential stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Each stage involves distinct biochemical transformations, culminating in the generation of biogas and microbial biomass. Figure 1 delineates the progression of these stages within the AD process.

The biological decomposition of organic substrates during anaerobic digestion is divided into four phases namely hydrolysis, acidogenesis, acetogenesis and methanogenesis [9]. These biochemical phases are directly linked in such a manner that the byproduct of one phase is the substrate of the next phase. They occur simultaneously in an oxygen-free environment and results in the formation of biogas and digestate as a byproduct [10] These biochemical decomposition phases are associated with a series of chemical reactions as shown in Equations in **Table 1**.

Table 1. Biochemical reactions associated with anaerobic digestion phases

AD Phase	**Associated Chemical Reactions**	**Ref.**
Hydrolysis	$C_6H_{10}O_4 + 2H_2O \rightarrow C_6H_{12}O_6 + 2H_2$	[11]
Acidogenesis	$C_6H_{12}O \leftrightarrow 2CH_3CH_2OH + 2CO_2$ $C_6H_{12}O_6 + 2H_2 \leftrightarrow 2CH_3CH_2COOH + 2H_2O$ $C_6H_{12}O_6 \rightarrow 3CH_3COOH$ $C_3H_7O_2N + 2H_2O \rightarrow C_2H_4O_2 + NH_3 + CO_2 + 2H_2 + ATP$ $C_4H_9O_3N + H_2O \rightarrow C_3H_6O_2 + NH_3 + CO_2 + H_2 + ATP$ $4CH_3COCOO^- + 4H_2O \rightarrow 5CH_3COO^- + 2HCO_3^- + 3H^+$	[12], [13], [14]
Acetogenesis	CH3CH2COO +3H2O CH3COO +H +HCO3 +3H2 Acetogenesis C6H12O6 + 2H2O 2CH3COOH+2CO2 +4H2 CH3CH2OH+2H2O CH3COO +2H2+H	[15]
Methanogenesis	CH3COOH CH4+CO2 Methanogenesis CO2 +4H2 CH4+2H2O 2CH3CH2OH+CO2 CH4+2CH3COOH	[16]

2.2. Process Simulation Via Aspen HYSYS & Aspen Plus

Some basis has been assumed as well as calculated to develop process simulation and to optimize sustainability of the Natural Gas **(Fig. 3)** & Bio Gas **(Fig. 4)**, which are shown in **Table A3 – A6** of Appendix Section.

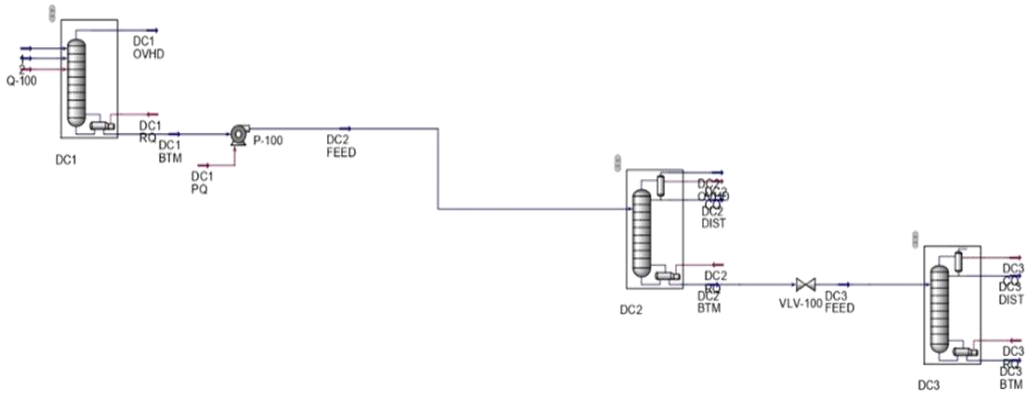


Fig. 3. Process modeling of natural gas using Aspen HYSYS

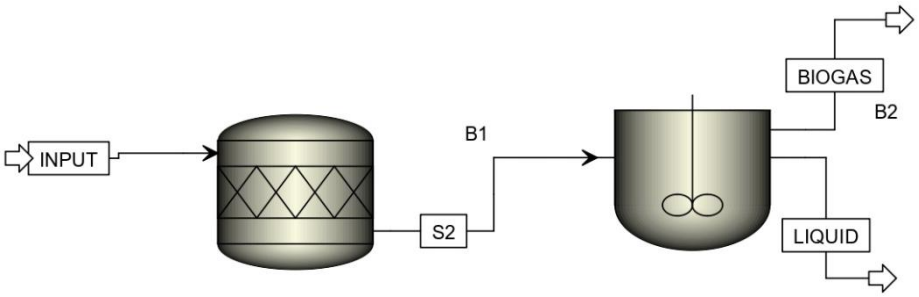


Fig. 4. Process modeling of bio gas using Aspen Plus

2.3. Indicator's calculation

The increasing demand for eco-friendly materials and services, driven by the need to reduce emissions, is exerting pressure on natural resources, necessitating a shift towards sustainable practices. In the chemical industry, this entails designing processes that minimize resource consumption and pollutant release while maintaining economic and social viability. By utilizing sustainability indicators, processes can be assessed and classified based on their environmental impact, guiding the development of both existing and new processes toward a more sustainable and resource-efficient future. [17].

3. Sustainability Analysis

Sustainability indicators are measurements that evaluate the environmental, social, and economic aspects of a system or process to establish its overall sustainability performance. Sustainable indicators are employed in the context of chemical processes to assess and quantify the environmental effects of different phases, from the procurement of raw materials to the disposal of finished products. These metrics aid in pinpointing problem areas and directing choices toward more environmentally friendly actions. Typically, four factors determine sustainable indicators: environment, economy, efficiency, and energy. In this study, environmental and efficiency indicators were studied to make our comparative analysis fruitful.

3.1. Comparative Assessment of Natural Gas & Biogas: Environmental and Efficiency Metrics

To simulate biogas extraction in Aspen Plus, several assumptions were applied: temperatures were set between 45°C and 60°C, with fermentation reactions modeled in Stoic reactors and acetogenesis, acidogenesis, and methanogenesis occurring in CSTRs under 1 atm pressure. Similarly, for natural gas extraction using Aspen HYSYS, temperatures ranged from 20°C to 55°C, with a pressure of 1 atm, utilizing three distillation columns of 10, 14, and 24 stages. Energy recovery was integrated at specific intervals, supported by a pump and valve system. Both biogas and natural gas simulations provided data on fractional components and flow rates, which were used to calculate environmental and efficiency metrics mentioned in **Table 2 & 3**, identifying optimal and suboptimal conditions based on comparative analysis.

Table 2. Calculation of environmental indicators for natural gas & bio gas

Indicators	Result		Metric	Sustainability Value	
	Natural Gas	Biogas		Best Target	Worst Case
Number of hazardous materials inputs	11 Metric value = 0.92	2 Metric value = 0.18	1	**0** ≅ 0.18 Low hazardous goods and services inputs in biogas	0.92 ≤ **1** High hazardous goods and services inputs in natural gas
Mass rate of hazardous materials input	35416.331	1.41373×10^{-5}	Kg/hr	Biogas: ≅ **0**	Natural gas:≫ **1**
Specific hazardous raw materials input	0.86	1.4×10^{-3}	Kg/Kg	Biogas: ≅ **0**	N.G: ≤ **1**
Health hazard, irritation factor	1.08×10^{-4}	0.070798	m3/kg	Biogas: ≅ **0** N.G: = **0**	-
Specific toxic release	0.245	1.94	kg/kg	NG: Small amount TRI toxic released	Biogas: Some TRI toxic released
Environmental hazard, persistency of organic substances	0.987	0.58	kg/kg	Biogas: 0 < 0.58 < 1	N.G: ≤ **1**
Global warming potential	9.038×10^{-3}	0.614	kg/kg	NG: = **0**	Biogas: ≤ **1**

Table 3. Calculation of efficiency indicators for natural gas & bio gas

Indicators	Result		Metric	Sustainability Value	
	Natural Gas	Biogas		Best Target	Worst Case
Total mass flow consumption	35758.5307	0.010098	kg/hr	N.G, Biogas: mass of product	-
Mass intensity	0.874	1	kg/kg	Biogas: = **1**	N.G.: < **1**
Mass productivity	0.874	1	kg/kg	Biogas: = **1**	N.G.: < **1**
Environmental factor	0.124	0.9806	kg/kg	N.G: ≅ **0**	Biogas: < **1**
Mass loss index	0.124	0.9806	kg/kg	N.G: ≅ **0**	Biogas: < **1**
Total water consumption	0	9.510^{-6}	m^3/h	N.G, Biogas = **0**	-
Fractional water consumption	0	9.410^{-4}	m^3/kg	N.G, Biogas = **0**	-

4. Result & Discussion

The results of the environmental indicators reveal significant differences between the natural gas and biogas production processes. Biogas showed a lower environmental burden with fewer hazardous material inputs (2 vs. 11 for natural gas), and a much smaller mass rate of hazardous materials (1.41×10^{-5} kg/hr for biogas compared to 35,416.33 kg/hr for natural gas). Biogas also had a lower health hazard factor (0.0708 m^3/kg) and specific toxic

release (1.94 kg/kg), while natural gas emitted fewer persistent organic substances and had a smaller global warming potential (9.038×10^{-3} kg/kg vs. 0.614 kg/kg for biogas).

Efficiency indicators showed that biogas is more resource-efficient than natural gas. Biogas had higher mass intensity and productivity (both 1 kg/kg for biogas compared to 0.874 kg/kg for natural gas), indicating a better conversion of input materials into the final product. Natural gas, on the other hand, had lower environmental and mass loss factors (0.124 kg/kg for both) compared to biogas (0.9806 kg/kg), suggesting that natural gas results in less waste. Both processes had negligible water consumption.

Overall, from **Figure 5** it is clear that biogas outperforms natural gas in most sustainability measures, especially in terms of hazardous material use and overall environmental impact. However, natural gas exhibits better performance in specific areas such as lower persistent organic emissions and waste reduction. These findings highlight that while biogas is generally a more sustainable alternative, further optimization is required to minimize its emissions and environmental hazards for it to become a fully sustainable energy source.

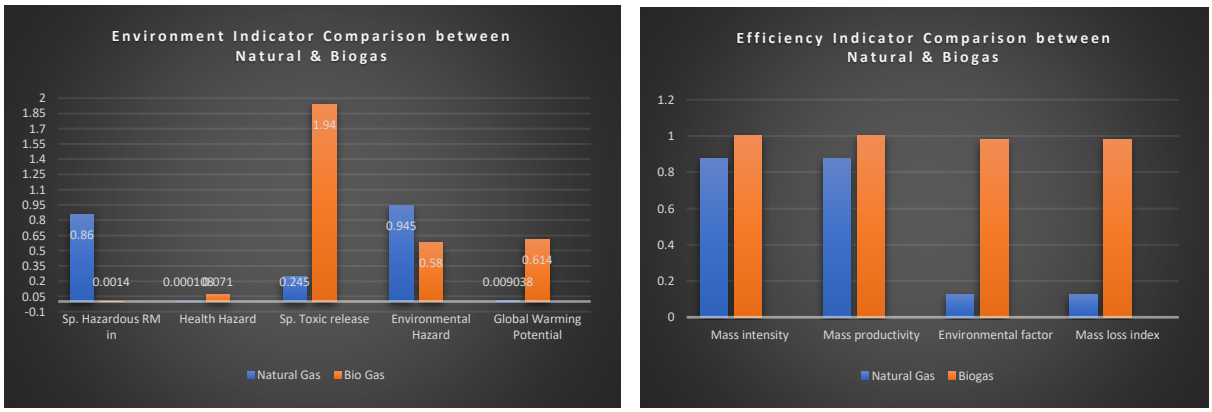


Fig. 5. Graphical representation of comparative analysis of sustainability indicators

5. Conclusion

To conclude, this study successfully addressed the objectives of mitigating rising energy demands and evaluating the sustainability of natural gas and biogas production processes. By comparing environmental and efficiency indicators, it was shown that biogas offers a more sustainable alternative to natural gas, with lower hazardous material inputs, reduced toxic emissions, and higher resource efficiency. These findings highlight the growing concerns about the environmental impact of natural gas and the pressing need for sustainable alternatives like biogas to meet future fuel demands while ensuring energy security.

The research demonstrated that biogas, despite its advantages, still requires optimization, particularly in reducing global warming potential and addressing residual toxic emissions. This reinforces the need for continuous development of biogas technologies to enhance its environmental performance and make it a more viable long-term energy solution. Additionally, while the study focused on environmental and efficiency indicators, future research should assess economic viability, energy efficiency, and safety considerations to provide a more comprehensive understanding of biogas as a sustainable fuel source.

Moving forward, it is essential to conduct a detailed assessment of economic and energy performance indicators, along with an overall safety analysis, to fully evaluate the feasibility of biogas as a large-scale fuel alternative. Further optimization of the biogas production process will also be crucial in ensuring that it can effectively compete with conventional fuels while minimizing its environmental footprint.

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Appendix