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Modern Status of Technology for Production of Highly Concentrated Methane by Biogas Purification

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Abstract: The current state of technology for obtaining highly concentrated methane by purification of biogas is an urgent problem in the context of sustainable development and reduction of greenhouse gas emissions. The study aims to investigate the methods and processes used to achieve a high degree of biogas purification with subsequent methane concentration. To achieve this objective, various techniques including the universal content analysis method, extrapolation method, systematic data analysis and comparative data analysis were used. The main results of the study show that global primary energy consumption increased by 1.4% in 2023. Meanwhile, natural gas consumption increased by 30% and renewable energy use increased by 7.1%. Studies show that biogas containing methane is highly efficient, for example in cooking (50%) and electricity generation (25%). Biogas upgrading technologies, such as chemical absorption cooling and ventilation, provide more than 98% purity of the CH4 product. The use of biogas methane instead of petrol significantly reduces emissions of harmful components such as CO, CO2 and UHC, improving air quality and reducing the negative impact on the climate. Biogas methane represents a promising energy source to contribute to sustainable energy development in the future. The practical significance of this study is that methane extracted from biogas not only has high efficiency but also reduces emissions of harmful components, improving air quality and reducing negative climate impacts. Its diverse origins, including organic waste, maximise resource efficiency, reducing methane emissions and contributing to clean energy production. Methane from biogas is highlighted as a promising energy source that plays an important role in sustainable energy development in the future.

Keywords: energy efficiency; ecology; organic waste; greenhouse gases; global consumption

1. Introduction

There has been an increasing interest in the use of biogas as a source of renewable energy since the early 2000s. This is due to the growing global awareness of the importance of reducing greenhouse gas emissions and finding alternative energy sources. Biogas projects provide a viable alternative to waste management, renewable energy generation, and sustainable agriculture. However, its execution necessitates careful consideration of economic issues. Small businesses require considerable upfront capital investment, which might be difficult owing to low financial resources. However, long-term benefits such as lower energy costs, better waste management, and possible revenue from the sale of excess energy or biofertilizer make these projects profitable. Government subsidies and incentives, public-private partnerships, microfinance possibilities, and community-based funding methods can all help biogas projects become financially sustainable. Biogas projects are scalable, allowing them to be adjusted to the individual needs and capabilities of small businesses. Integrating biogas systems with existing agricultural methods can increase economic feasibility.[1)-6)] Increasing greenhouse gas emissions, climate change and threats to the environment have pushed many countries to search for alternative energy sources with low carbon dioxide emissions. Biogas, mainly consisting of methane, is considered to be more environmentally friendly compared to fossil fuels.[7)-13)] As noted by B. Bakhtiyar et al.[14)], biogas production can become an additional source of income for agricultural enterprises. Methane produced from agricultural waste can be used for electricity generation, heat production, or even transport. Meanwhile, D. Esenzhol et al.[15)] argue that the utilisation of biogas in agriculture can also contribute to sustainable energy in rural areas. It can be used for heating homes, drying crops, and even for powering agricultural machinery.

Many governments are introducing national and regional programmes to support biogas production and use. These programmes include financial incentives, tax breaks and regulations to promote the development of the industry. Modern technologies allow for more efficient extraction of methane from biogas and its use in various industries, including power generation, heating, and motor vehicles. This makes biogas more affordable and competitive.[16)-21)] S.B. Zhaparova et al.[22)] concluded that biogas utilisation helps to reduce the amount of waste that is sent to landfills and reduces greenhouse gas emissions as the methane that was previously emitted into the atmosphere is now used as fuel. This helps to reduce the negative impact on the environment and contributes to the achievement of sustainable development goals.

Biogas initiatives have several social advantages, such as better living circumstances in rural areas, economic empowerment, environmental sustainability, and gender equality. By offering a clean, renewable energy source, biogas lowers dependency on traditional biomass fuels, which have been linked to indoor air pollution and respiratory health problems. This move has the potential to improve health outcomes for rural communities, particularly women and children who are traditionally responsible for cooking and obtaining fuel.[23)] Biogas projects also increase local job prospects by providing trained and semi-skilled labour, encouraging entrepreneurial activity, and strengthening rural communities' economic resilience. They also contribute to better organic waste management, which reduces pollution and promotes cleaner environments. The collaborative nature of biogas initiatives creates social cohesion and shared responsibility among community members.[24)] Furthermore, biogas projects can promote gender equality in rural regions by making energy more accessible and efficient, allowing women to devote more time to other economic activities.

T.S. Baizhumanova et al.[25)] argue that highly concentrated methane produced from biogas can be used in various areas of urban infrastructure. This includes its use in urban vehicles to power buses or rubbish trucks, as well as in heat and power generation to heat buildings and supply urban networks. At the same time, G. Tursunbayeva et al.[26)] reported in their research that highly concentrated methane is an effective alternative heat source for industrial plants, which can replace traditional fossil fuels such as natural gas and fuel oil. This reduces carbon dioxide (CO_2) emissions and saves on energy costs. In addition, highly concentrated methane can be used to produce chemical products, reducing the dependence on oil and natural gas in the chemical industry. However, the process of producing highly concentrated methane from biogas requires stability and reliability. Equipment malfunctions or reduced quality of biogas supply can lead to inefficiencies and unplanned shutdowns. Distributing biogas as a fuel requires adequate infrastructure, including liquefied natural gas, plants, and pipelines. The development of this infrastructure requires significant investment and planning.[27)-32)] The implementation of modern technologies to produce highly concentrated methane from biogas often requires significant capital investments, which may not be affordable for small enterprises and regions with limited financial resources.[33)-37)]

The purpose of this research is to provide a comprehensive analysis of the role of biogas, specifically methane, in advancing sustainable energy solutions. Objectives of this research include:

1. Assess existing technologies for creating biogas from organic waste, biomass, and animal manure.
2. Examine the environmental impact of biogas usage vs traditional fossil fuels.
3. Evaluate the economic viability of biogas production and utilisation.
4. Identify and evaluate potential technologies and feedstocks to improve biogas production and efficiency.
5. Review current policies and laws regarding biogas production and use.

2. Research design and analytical techniques

The following scientific methods and approaches were applied to achieve the set objectives and analyse the current state of technology for the production of highly concentrated methane by biogas purification: universal content analysis method, extrapolation method, systematic data analysis and comparative data analysis. One of the key components was the selected method of universal content analysis of the international database of organisations. This method highlights the key concepts, principles and technical characteristics needed to analyse and develop new approaches to process improvement. This method was used to search and analyse all available published material on the topic of interest. Research from major centres and universities was also included in the analysis.

The extrapolation method is a forecasting methodology that employs historical data and observed patterns to project future trends in the biogas and methane production industries. It aids in forecasting advancements by examining existing technology, market dynamics, and manufacturing efficiency. This strategy is critical for biogas sector stakeholders because it allows them to plan for market changes, such as increased demand for highly concentrated methane. Extrapolation, which uses data on production levels, technology adoption rates, and market pricing, offers a clear picture of probable future scenarios, allowing for better strategic planning and investment decisions. Technological advancement is particularly important in these forecasts since it allows for predicting how improvements in biogas and methane production technologies will affect production efficiency and environmental performance. Extrapolation, for example, may predict how advances in biogas digesters or methane purification technology would affect future methane production and energy inputs. The extrapolation approach categorises and analyses data based on criteria such as biogas composition, energy inputs, and environmental effect, allowing for the discovery of critical components impacting methane production efficiency. This extensive research allows for more accurate projections and helps the sector focus on optimising certain areas of the manufacturing process.

Comparative analysis was carried out to identify which approaches and technologies are now the most promising and may be employed to obtain best outcomes in methane generation and biogas purification. The method was used to evaluate the efficiency of different modern technologies for the production of highly concentrated methane by biogas purification. Analysing the yield of methane produced provided information on the amount of methane that can be extracted from biogas using different methods and technologies. This assessment allowed the identification of the most productive approaches capable of maximising productivity in the methane production process. The methane loss study was aimed at identifying possible methane losses during the purification and production process. Assessment of the degree of purification of biogas from impurities was aimed at determining the effectiveness of methods and technologies in removing unwanted components from biogas. This was used to determine how clean methane can be produced using different methods and thus to compare their effectiveness in this regard, namely, to determine the yield of methane produced, its losses and the degree to which the biogas is cleaned of impurities.

3. Comprehensive evaluation of biogas: From production processes to environmental outcomes

3.1 Global energy consumption trends and the role of biogas

According to a report by International Energy Agency,[38] global primary energy consumption continued its growth in 2023, increasing by 1.4%. It is important to note that the most significant contribution to this growth was made by natural gas, whose consumption increased by almost 30%, and renewable energy sources, whose increased consumption accounted for 7.1% of the global energy balance.[39] Biogas, in particular methane, plays a significant role in this process. It is a powerful source of energy that can be obtained from various sources such as organic waste, biomass and even animal manure. Its utilisation has dual benefits: firstly, it reduces waste and environmental impact, and secondly, it provides an efficient source of renewable energy.

Biogases serve as essential for Europe's energy sector's decarbonisation. In 2022, Gas for Climate projected the possibility for biomethane generation in the EU-27 in 2030 and 2050. The European Commission has set a target of producing 35 billion m^3 of biomethane per year by 2030, a tenfold increase over current output. This document by Alberici et al.[40] updates the 2022 Gas for Climate research by focussing on 2040 and estimating the potential for biomethane generation in Europe. According to the most recent estimates, Europe may produce up to 44 billion m^3 of biomethane in 2030 and 165 billion m^3 by 2050. By 2040, Europe may generate 111 billion m^3 of biomethane, with the EU-27 accounting for 101 billion. Sequential crops, animal manure, agricultural residues, industrial wastewater, wood waste, municipal solid waste's organic portion, and forestry residues are crucial feedstocks. Novel feedstocks, including marginal or polluted areas, seaweed, digestate, hydrothermal gasification, renewable methane, and landfill gas, might uncover more possibilities. This article presents qualitative insights into how each of these can help to ensure sustainable biomethane production in 2040 and beyond.

Anaerobic digestion of organic feedstocks yields biogas and digestate (also known as biofertilizer) as coproducts. Digestate is a nutrient-dense organic substance.[40] It comprises the three essential macronutrients for plant growth: nitrogen (N), phosphorus (P), and potassium. Secondary nutrients include magnesium (Mg), calcium (Ca), and sulphur (S), as well as micronutrients like copper (Cu) and zinc (Zn). Digestate can therefore be used as an agricultural fertiliser, substituting synthetic fertilisers.

Forecasts by International Energy Agency[38] indicate that global energy consumption will continue to grow and is expected to increase by 50% by 2050 compared to 2023. The most notable trend in this process will be the growth of renewable energy. This leap in renewable energy use is made possible by strategic public policy efforts to decarbonise the housing and transport sectors. This will reduce CO_2 emissions and increase the sustainability of the global energy system. The transition to biogas, including methane, and other renewable energy sources represents an important stage in the development of modern energy infrastructure, with significant importance in the context of global strategies to reduce dependence on fossil energy resources and minimise negative impacts on the environment and climate processes. In this context, the prospective use of biogas and its components, as well as other renewable energy sources, is considered as key components in transforming the energy industry into a more sustainable and environmentally friendly system that contributes to the well-being of future generations.[41)-45)]

3.2 Composition of biogas from various sources

Based on the reports of International Energy Agency,[38)] detailed information on the composition of biogas has been collected, considering its diverse origins and therefore chemical composition depending on the feedstock source and processing (Table 1). The availability of data on the composition of biogas is important to assess its potential as an energy resource and to develop appropriate technological solutions.

Table 1. Biogas composition depending on its origin.

Gas	Agriculture waste (%)	Water treatment plant waste (%)	Manufacturing waste (%)	Landfills (%)	Reaction
Methane	45-73	45-73	50-70	45-65	Combustible
CO_2	30-50	31-62	30-50	34-55	Passive
H_2	0-3	0-5	0-2	0-1	Combustible
H_2S	100-9000 parts/mln	0-1	0-8	1-2500 parts/mln	Corrosive
NH_3	42-125 mg/m²	Marks	Marks	Marks	Corrosive
CO	0-2	0-1	0-1	Marks	Combustible
N_2	0-1	0-3	0-1	0-20	Passive
O_2	0-1	0-1	0-1	0-5	Corrosive

Source: compiled by the authors.

From analysing information on the composition of biogas depending on its origin, it can be seen that the composition of biogas can vary considerably depending on the type of waste. However, regardless of origin, biogas always contains methane in the range of 45% to 73% and CO_2 in the range of 31% to 62%, although their concentrations vary. Methane has combustible properties. Additional biogas components include hydrogen (0-3%), hydrogen sulphide (0 to 9000 parts/mln), ammonia (42 to 125 mg/m²), carbon monoxide (CO) (0-2%), nitrogen (in traces up to 3%) and oxygen (0-5%), with their contents also varying from source to source. These components can have different applications and are important from a safety point of view, as some of them can be corrosive or flammable gases.

3.3 Different applications of biogas

According to the International Energy Agency, biogas extracted from organic materials is a potentially important energy source that can meet a variety of societal needs. By analysing the data provided, the biogas requirements for different applications were assessed and the approximate amount of biogas required to offset the energy demands was determined (Table 2).

Table 2. Biogas demand for different applications.

Usage	Transformation efficiency (%)	Biogas volume
Cooking	50	0.3-0.4 m³/day/person
Indoor lighting	4	0.12 m³/hour/100 candlelight output
Electricity generation	20	0.6 m³/kWh (dual-fuel engine)
	25	0.75 m³/kWh (biogas engine)

Source: compiled by the authors.

The study of information on biogas consumption for various purposes emphasises the significant advantage of using biogas as an energy resource. The efficiency of biogas conversion can be relatively high, as in the case of cooking (50%) and electricity generation with a biogas engine (25%). This means that biogas maximises the use of available resources and minimises losses. Furthermore, it should be noted that the use of biogas for indoor lighting, although characterised by low efficiency (4%), has the potential to improve environmental performance. For example, only 0.12 m³ of biogas per hour is required to power 100 candles of light, indicating its relative cost-effectiveness in this context compared to other energy sources that may be less environmentally friendly. Biogas is thus a clean, efficient, and versatile resource that can contribute to sustainability and environmental protection while meeting energy needs.

3.4 Methane yield from various biomass materials

According to the World Meteorological Organisation, methane, as an important component of biogas, represents a valuable source of renewable energy and its recovery from biological materials is one of the key challenges for sustainable energy and waste management.[46)-49)] Analysing the data, an overview of the methane content (mln m³) for different substrate types is provided (Table 3). These indicators can be useful for decision-making in the planning and optimisation of biogas production processes, as well as for bio-waste management to reduce environmental impacts and maximise the use of methane as a renewable energy source.

Table 3. Methane yield overview for different substrate types.

Biomass material	Contents (mln m³)
Fruit and vegetable leftovers	550-620
Cattle excrement	160-207
Cattle manure	259-340
Food waste	284-462
Sewage sludge	203-326
Poultry slaughter waste	520-556
Fish waste	329-472
Slaughterhouses	500-592
Biological oil	306-421

Source: compiled by the authors.

The results show that different substrate types have different methane contents in millions of cubic metres (mln m³). Substrates such as fruit and vegetable waste (550-620 mln m³) and poultry slaughter waste (520-556 mln m³) have a high potential for methane release. Agricultural materials such as cattle excreta (160-207 mln m³) and cattle manure (259-340 mln m³) can also be significant sources of methane. Food waste (284-462 mln m³) and bio-oil (306-421 mln m³) also contribute to methane emissions. Sewage sludge (203-326 mln m³) and fish waste (329-472 mln m³) release less methane than other substrates but can still be significant. These data emphasise the importance of managing and utilising biological waste for sustainable methane production and reducing negative environmental impacts.

3.5 Biogas engine performance in Kazakhstan

A study conducted at the Almaty University of Energy and Communications in Almaty, Kazakhstan, focused on the potential for electricity generation from biogas produced from the biological decomposition of organic materials. This study applied an advanced technology based on the treatment of the produced biogas using 0.5 M sodium hydroxide (NaOH) solution to achieve a high degree of purification and enrichment of the gas mixture to produce methane-rich products. The engine performance was analysed thoroughly and is presented in Table 4. The obtained pure methane, after completion of the treatment process, was used as an internal combustion fuel in a specially prepared engine.

Table 4. Technical characteristics of the engine

Engine type	Single-cylinder, four-stroke
Power	850 W
Displacement	100 cm³
Fuel type	Petrol
Starter type	Knockback system

Source: compiled by the authors.

Table 5 shows the impact of methane produced in the biogas treatment process and potentially used as an alternative fuel to petrol on CO, CO_2 and unburned hydrocarbon (UHC) emissions.

Table 5. Biogas methane and petrol impact on engine pollution.

	CO_2 (vol. %)	UHC (parts/mln)	CO (vol. %)
Biogas engine	0.8394	115.916	0.2519
Petrol engine	1.7143	182.05	1.4803
Change in methane compared to oil	-50%	-37.41%	91.33%

Source: compiled by the authors.

The data obtained show the effect of methane gas obtained in the process of biogas purification and used as an alternative fuel for petrol on emissions of such harmful components as CO, CO_2 and total UHC. The use of methane gas extracted from anaerobic processes of animal organic residues processing leads to a marked reduction in the emissions of the above polluting components by 50%, 91.33% and 37.41%, respectively, compared to the use of petrol in the same fuel context. This effect is attributed to the significant reduction in the amount of carbon contained in methane compared to petrol. In summary, the use of purified biogas in a generator engine has a positive environmental impact, reducing greenhouse gas emissions compared to the use of petrol in the same operating context.

The findings demonstrate an innovative purification technology that significantly improves methane's usefulness as an alternative fuel. This purification procedure, which employs sodium hydroxide, not only enhances methane content but also reduces emissions of dangerous contaminants.

The more than 90% reduction in CO emissions suggests a significant increase in the engine's methane combustion efficiency. This finding shows that methane's chemical features enable a more efficient and cleaner combustion process, perhaps leading to fewer health hazards associated with CO exposure. The significant reduction in CO_2 emissions underlines methane's environmental benefits as a lower-carbon fuel option, which aligns with larger climate action goals targeted at lowering greenhouse gas emissions.

The observed reduction in UHCs indicates that methane combustion generates less incomplete combustion byproducts. This reduction not only improves air quality, but it also shows that methane-powered engines may have increased operating efficiency, perhaps leading to longer engine life and fewer maintenance requirements.

This gives significant evidence for the potential of biogas-derived methane as an environmentally acceptable fuel. The enhanced emission profile may support policies that promote alternative fuels and stimulate more research into biogas technology. The findings may increase corporate interest in using methane as a mainstream alternative to petrol, promoting both environmental and public health advantages.

3.6 Comparison of biogas upgrading technologies

The Intergovernmental Panel on Climate Change (IPCC) has provided information related to the assessment of product purity and methane losses in the context of various technological solutions used to improve biogas production. An analytical review of this information provides an opportunity to compare the performance of different technologies in terms of their impact on final product quality and methane leakage (Table 6). This is important in the context of deciding on optimal modernisation strategies for biogas plants, given the specific challenges and operating conditions.

Table 6. Product purity and methane losses for different biogas upgrading technologies.

Production technologies	**Basic functioning principle**	**Gas purity of CH_4 (vol. %)**	**Concentration of CO_2 (vol. %)**	**CH_4 losses (%)**
Cooling and ventilation	Compression and decompression	98.01	100	0.005
Water treatment	Physical friction	94-98	83-92	<2
Physical absorption	Physical friction	92-98	-	<4
Chemical absorption	Physical friction	>98	91-94	<0.5
Cylindrical absorption	Absorption	>95-98	77	<3
Membrane barrier filtration	Penetration	92-99	-	<5
Methane content optimisation in the reservoir	Absorption/desorption	96	-	<8

Source: compiled by the authors.

Analysis of information presenting product purity and methane losses of different biogas upgrading technologies shows that most of them provide high CH_4 product purity, which is important for efficient biogas utilisation. Technologies such as chemical absorption cooling and venting show the highest CH_4 product purity (more than 98%) and minimum methane losses (less than 0.5% and 0.005%, respectively). However, other techniques such as membrane barrier filtration and cyclic adsorption also offer good product purity and relatively low methane losses (less than 5% and less than 3%). The choice of the optimal technology depends on the specific conditions and product purity requirements, but based on the data presented, it can be concluded that several effective biogas upgrading methods achieve high product purity and minimise methane losses.

The data demonstrates the relevance of biogas, particularly methane, in global energy dynamics. As energy demands increase, the transition to renewable sources and the optimisation of current technology becomes critical. Biogas addresses two major issues: environmentally friendly waste management and the development of renewable energy sources.

The emphasis on innovative feedstocks such as seaweed and hydrothermal gasification demonstrates the biomethane industry's drive for innovation. These developments indicate a significant chance to improve the efficiency and scalability of biogas generation. As new technologies and feedstocks are developed, biogas's ability to contribute to the energy mix expands, providing a flexible and adaptable resolve to energy concerns.

The increasing prevalence of biogas in the energy landscape also indicates a trend towards more localised and resilient energy systems. Biogas technology, which decentralises energy production and uses local waste resources, can improve energy security and reduce reliance on foreign fuels. This localised strategy not only promotes sustainable development goals, but also complements larger initiatives to establish more self-sufficient and ecologically friendly energy systems.

As global energy demand develops, biogas will play an increasingly essential role. Its ability to generate clean, renewable energy while also addressing waste management and encouraging a circular economy makes it an important component of future energy infrastructure. As technology advances and regulatory frameworks improve, biogas has the potential to play a significant role in fulfilling the world's expanding energy demands in a sustainable way.

4. Discussion

Since the early 19th century, with the advent of man-made energy sources, fossil fuels have been the dominant global source of energy, providing the necessary power for industrialisation, modern comfort levels and meeting consumer needs.[50)] However, over time, awareness of the environmental and climate impacts of fossil fuels has increased, and this has emphasised the urgent need for a global transition to more environmentally sustainable energy sources.[51)-62)]

Biogas adoption on a worldwide scale requires a well-crafted governmental framework as well as economic incentives. Researchers like L.A. Díaz-Trujillo and F. Nápoles-Rivera[63)] emphasise the necessity for optimising biogas supply networks in underdeveloped nations, taking into account economic and environmental concerns. They propose that customised policies address regional problems such as feedstock supply and financial resource availability in order to improve the feasibility and scalability of biogas plants. Economic incentives, such as feed-in tariffs, tax breaks, and subsidies, are critical for overcoming financial hurdles to biogas adoption, according to J. Edwards et al.[64)] They emphasise the effectiveness of feed-in tariffs, tax incentives, and subsidies in making biogas projects profitable. Research by Z. Gebreegziabher et al.[65)] on urban biogas installations in Sub-Saharan Africa reveals that policies that promote biogas integration into waste management systems can improve urban sustainability. Additionally, this provides a reliable source of renewable energy.

O.J. Odejobi et al.[66)] state that climate change has a profound impact on the ecological environment. The author points out that the emission of greenhouse gases such as carbon dioxide resulting from the burning of coal, oil and natural gas contributes significantly to global warming and climate change. This phenomenon leads to an increase in the frequency and intensity of weather-related disasters, sea level rise and other consequential effects of enormous magnitude.[67),68)] The burning of fossil fuels additionally leads to air pollution, endangering human health and ecosystems. Moreover, fossil fuels are a finite resource that will be depleted over time. M. Gustafsson and S. Anderberg[69)] also note the importance of transitioning to cleaner energy sources in the context of growing global energy consumption. Solar and wind energy, as well as other renewable energy sources, play a key role in reducing carbon dioxide emissions and reducing dependence on traditional fossil energy sources. They have many advantages, including low environmental risks and an infinite potential supply.

P. Rani et al.[70)] confirm the above-mentioned conclusions regarding the correlation between the growth of energy consumption and the expansion of the world economy. It is worth noting that such a correlation is present in the modern world and reflects the growth of consumer and production needs. Nevertheless, the author emphasises the importance of transitioning to sustainable and green economic growth in light of the challenges of climate change and environmental sustainability. To achieve this goal, the author cautions the need for substantial investments in the development and deployment of efficient technologies that would help to reduce negative environmental impacts. In addition, improving energy efficiency plays a critical role in reducing energy consumption and hence greenhouse gas emissions. Incentivising sustainable consumption and production practices is also an integral part of achieving environmental sustainability in the context of economic growth. The findings of the study are consistent with the conclusions presented in the works of the authors mentioned above. In sum, the transition to cleaner energy sources not only contributes to reducing negative environmental impacts but also contributes to a more sustainable and reliable energy system for future generations. This represents a challenge that the global community must address through joint efforts, cooperation, and innovation.[71)-79)]

The study by Chmielewski et al.[80)] presents significant findings related to the enrichment of biogas, particularly focusing on the challenges posed by micropollutants such as silanes. Remarkable changes in the concentration of various chemicals in biogas produced in plants utilising different substrates and operating under different circumstances were reported. The maximum biomethane content was reported when sludge from a municipal waste water plant was used as a substrate (over 65% v/v). In three additional cases, the reported CH4 content ranged from 50 to 52% v/v. The gas recovered from municipal landfills has a high nitrogen content (more than 16% v/v). Aside from a high concentration of nitrogen, gaseous products collected from landfill wells contain BTEX chemicals (although the quantity of benzene is not excessive in this and three other cases) and siloxanes. This type of fuel appears to be suitable for both heating and power generation after primary purification, as cogeneration systems are the most cost-effective. Organic silicon compounds are listed as the most undesirable compounds affecting energy utilisation in biogas produced from waste materials, because silica particles formed during the combustion process and deposited on the mechanical internal parts of the generator may cause wear of movable elements. These semi-volatile organosilicon compounds are employed in a variety of industrial and consumer applications, including shampoo, cosmetics, and lubricants. As a result, they can be found in municipal waste landfills and wastewater plant effluent, where they volatilise into landfill gas or digester gas in the latter case. Interestingly, identical trace quantities of mercury were found in all of the examined instances. Air pollution from coal-fired power stations and household furnaces/boilers may be the source.

B.A. Osei-Owusu et al.[81)] concluded in their studies on the potential of biogas as an energy source that biogas has a high conversion efficiency into energy, especially when used in cooking and power generation. This indicates its significant potential to fulfil a variety of energy needs. These conclusions are in line with the results of existing research. In contrast, colleagues from Northern Ethiopia, H. Fentie and G. Sime[82]), concluded on the practicality of biogas production. The authors concluded that biogas can be produced from various organic materials such as fruit and vegetable waste, livestock excreta and food waste. This makes it possible to efficiently utilise resources that were previously thought to be untapped or even problematic to dispose of. By turning these wastes into biogas, pollution can be reduced, and energy can be generated at the same time. The study's conclusions are in line with the data. Simultaneously, A. Soltanzadeh et al.[83]) confirmed that the use of biogas from organic materials also helps to reduce methane emissions into the atmosphere. Methane is a potent greenhouse gas, and its reduction has a positive impact on combating climate change. The results of the study draw similar conclusions. The results of the study, in particular, showed that using methane from biogas instead of traditional fuels such as petrol or diesel is one way to reduce environmental impacts and combat climate change. It is an important part of sustainable and clean energy solutions.

K.T.X. Tong et al.[84]) confirm the previously formulated principles presented in the authors' work, emphasising the significant advantages of methane as a cleaner fuel compared to petrol and diesel in their conclusions. One of the key aspects of this comparison is the lower carbon dioxide emissions from methane combustion. This factor has a positive impact on reducing humanity's contribution to global climate change, a critical issue for modern ecology and sustainable development. Similar results were achieved by researchers B.A. Parra-Orobio et al.[85]) in a study. According to their analysis, methane combustion, in addition to reducing carbon dioxide emissions, is also characterised by a lower formation of particulate matter, which can pose a potential threat to human health and is an important aspect of reducing atmospheric pollution. These results emphasise not only the environmental importance of methane as a fuel but also its potential benefits in providing a cleaner and healthier atmospheric environment.

D.D. Sapariya et al.[86]) resorted to the gasification method to purify biomass. The authors consider this method as an advantage as it allows the utilisation of a variety of feedstock sources including coal, wood, biomass, and waste and has the potential to reduce CO_2 emissions compared to the use of traditional fossil fuels. However, it should be noted that gasification requires substantial investment in infrastructure and faces technical and economic challenges that can be overcome with technological development and research. D.C. Makepa et al.[87]) used the pyrolysis method for waste treatment. The author mentioned this method as highly effective in reducing waste. Pyrolysis can be applied to treat a variety of wastes including plastic, rubber and other materials that might otherwise pose a problem for disposal. This process helps to reduce the negative environmental impact and promotes recycling of materials. In addition, the author notes that the synthesis gas produced by pyrolysis includes methane, CO, hydrogen (H_2) and other gases. This synthesis gas can be purified and converted into methane, which can be used as a fuel or raw material for various manufacturing processes.[88)-106)]

Consequently, fossil fuels are causing a serious problem due to methane emissions.[107),108)] This gas is a potent greenhouse gas and its levels in the atmosphere have a significant impact on climate change. Switching to clean energy sources, including biogas, is key as it reduces methane emissions and helps to combat climate change. Biogas produced from organic materials not only reduces pollution but also provides an efficient energy source that can be used for a variety of energy needs. It is an important component of sustainable and environmentally friendly energy solutions.

5. Conclusions

The study emphasises the importance of biogas, particularly methane, in promoting sustainable energy options while reducing environmental effect. Biogas generation from organic waste and other feedstocks has a dual benefit: it tackles waste management issues while also providing a sustainable energy source that may contribute to energy security. As global energy consumption patterns alter, including biogas into the energy mix appears as a vital method for balancing energy demands and environmental sustainability.

The study emphasises the growing relevance of biogas in light of rising global energy demand and the changing role of renewable energy sources. With natural gas and renewable energy gaining popularity, biogas provides a viable answer for reducing dependency on fossil fuels while minimising environmental deterioration. Biogas technology, which converts organic waste into energy, covers both waste management and energy generation, establishing itself as a vital participant in sustainable development.

In Europe, biogas, particularly biomethane, is critical for meeting aggressive decarbonisation targets. The European Union's biomethane production objectives highlight the sector's tremendous development potential. Leveraging a varied variety of feedstocks, from agricultural residues to municipal waste, can open up fresh opportunities for expanding biomethane production. This growth contributes to larger initiatives to reduce greenhouse gas emissions and increase renewable energy use.

The study demonstrates the importance of biogas as a sustainable energy source. It encourages ongoing investment and research to improve biogas production and integration into the energy system. This allows us to work towards a more sustainable energy future while effectively addressing both environmental and energy issues.

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