



Biogas as a Tool for Climate Change Mitigation: Greenhouse Gas Reduction Pathways

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ABSTRACT

Climate change remains one of the major environmental challenges facing the world today. It results predominantly from greenhouse gas (GHG) emissions from anthropogenic activities such as in production of energy, agriculture and industrial activities. The technology using biogas is a renewable energy source that us gotten from the anaerobic digestion of organic materials and offer the benefits of waste management and climate change mitigation. This review paper presents the role of biogas in reducing methane (CH₄), nitrous oxide (N₂O), and carbon dioxide (CO₂) emissions through sustainable waste utilization, fossil-fuel substitution, carbon sequestration, and nutrient recycling. The study analyses the contribution to GHG mitigation, lifecycle emission comparison with conventional fossil fuels, policy and economic drivers, and associated technological innovations. Evidence shows that biogas systems have the capacity to reduce methane emissions by up to 70–90% from agricultural waste streams, offset 30–80% CO₂ through energy substitution, and reduce inorganic fertilizer demand, consequently lowering N₂O emissions. Challenges including feedstock inconsistency, high installation cost, lack of technical expertise, and policy bottlenecks are also discussed. The review concludes that large-scale integration of biogas systems into national energy transitions can significantly contribute to climate targets under the Paris Agreement. Recommendations highlight scalable pathways for implementation in developing economies, financing models, and innovations such as upgraded biomethane, digestate valorization, and AI-based process monitoring for efficiency improvement.

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LIST OF ABBREVIATIONS

Anaerobic Digestion (AD)
 Combined Heat and power (CHP)
 Global Warming Potential (GWP),
 Greenhouse gas (GHG)
 Intergovernmental Panel on Climate Change (IPCC)
 Liquefied Petroleum Gas (LPG)
 National Biogas and Manure Management Programme (NBMMP).
 Palm Oil Mill Effluent (POME).

1.0 INTRODUCTION

Global warming results from increased greenhouse gas gases in the atmosphere which poses serious risks to the environment (Ramesh 2025). These are shown as heatwaves, increasing sea levels, loss of biodiversity and extreme events of weather parameters (Rossati 2016). The major source of energy in the world is fossil fuels and it accounts for over two-thirds of global emissions of carbon dioxide. The paradigm shift to renewable energy is very important in the stabilization of climate and meeting the global target of Net-Zero greenhouse gas by 2050. Climate change has several environmental risks and the key driver to this phenomenon is the increases greenhouse gases such as carbon dioxide, methane and nitrous oxide (Nunes 2023). Transition into the use of renewable and energy with low carbon content is critical as the energy sector accounts majorly (more than 70%) of global emissions.

A sustainable approach to climate mitigation is the production of biogas. It reduces methane emissions which are released during organic waste decomposition and efficiently convert biomass to energy. This has made biogas an important tool for sustainable environment, diversification of energy and reduction of wastes. Biogas production process involves the anaerobic digestion (AD) approach of organic waste such as manure from animals, sewage sludge, residues from crops, waste from food, and effluents from industrial biomass. Biogas technology provides a waste-to-energy platform that is integrated and involves capturing methane and its utilization rather than released into the atmosphere. This approach differs from renewable sources that are conventional which provides clean energy. With this, biogas can be positioned as a strategic tool in reducing methane, carbon dioxide and nitrous oxide emissions from the agricultural, industrial and municipal sectors. Hence, this review evaluates the production processes of biogas and feedstock pathways, impacts on reduction of greenhouse gases, technological innovations for mitigation, and the future research opportunities.

2.0 GLOBAL CONTEXT OF CLIMATE CHANGE AND GREENHOUSE GAS EMISSIONS

Climate change is one of the most critical environmental challenges that has occurred in the 21st century. It has been primarily caused by the increase in the greenhouse gases concentration in the atmosphere (Lewis et al., 2017). Human activities such as the burning of fossil fuels, industrial processes, deforestation, and agricultural practices that are unsustainable have increased the natural greenhouse effect, resulting in accelerated global warming (Shivanna 2022). In the last century, the average temperatures globally have significantly increased and has been projected to increase if emissions are not checked (Yuan et al., 2024). It was warned by the Intergovernmental Panel on Climate Change (IPCC) that it is important to prevent the rise of global temperature beyond 1.5°C and can be achieved through the integration of renewable energy, the process of rapid decarbonization, and land management practices that are sustainable (Santos et al., 2022).

2.1 Major Greenhouse Gases

The concentration, global warming potential (GWP), and persistence of greenhouse gases vary in the atmosphere (Dwivedi et al., 2022). The major greenhouse gases are carbon dioxide, methane and nitrous oxide. Carbon dioxide is the most abundant in the atmosphere and is due to the large-scale combustion of fossil fuels; and, it is less potent per molecule. Methane is released majorly from the decomposition of wastes, livestock, and activities from agricultural processes. It has a GWP that is approximately 28–34 times and 80 times more than carbon dioxide over a 100-year period and short term respectively (Kabange et al., 2023; Ghassemi et al., 2024). Nitrous oxide is mainly released from fertilizers that are synthetic in nature and burning of biomass. It has a higher GWP which is almost 300 times that of CO₂ (Rahman and Forrestal 2021). A summary of characteristics of greenhouse gases is presented in Table 1.

The dominance of carbon dioxide in total emissions and the potency of methane and nitrous oxide emphasizes the need for mitigation approaches to address all major sources of greenhouse gases (Nunes 2023). With this, biogas technology becomes very relevant as it can reduce the emissions of methane and nitrous oxide while offering an alternative as a renewable energy source (Xing and Wang 2024).

Table 1: Greenhouse gases and their characteristics

Greenhouse Gas	Primary Sources	Approximate Atmospheric Lifetime	Global Warming Potential (GWP) relative to CO ₂
Carbon dioxide (CO ₂)	Fossil fuel combustion, deforestation	100–1000 years	1
Methane (CH ₄)	Agriculture, landfills, wastewater, livestock	Approximately 12 years	28–34
Nitrous oxide (N ₂ O)	Fertilizers, biomass burning, industrial processes	Approximately 114 years	265–298
Fluorinated gases	Refrigeration, industry, aerosols	Up to thousands of years	1000+

Source: Nunes (2023).

2.2 Sectoral Contributions to Global Emissions

The largest contributor to the emission of greenhouse gases is the energy sector and it accounts for over two-thirds of global carbon dioxide output (Askr et al., 2024). Most of the methane and nitrous oxide emissions are from agriculture, especially from enteric fermentation, application of fertilizer and management of manures (Werku et al., 2025). Some other emitters of greenhouse gases especially methane from the anaerobic

degradation of organic matter in the waste sectors, which includes landfills and wastewater treatment (Chidibere-Mark et al., 2022). Carbondioxide and other fluorinated gases can be added to the atmosphere through industrial activities such as the production of cement, manufacturing, and processing of chemicals which can intensifying warming of the atmosphere (Feliciano et al., 2022). Some of the sectors and global emissions are presented in Table 2.

Table 2: Sectorial contributions to global emissions

Sector	Main Emissions	Relative Contribution to GHGs
Energy production	Carbondioxide from fossil fuels	Highest contributor globally
Agriculture	Methane and Nitrous oxide	Significant share of non-carbondioxide gases
Waste management	Methane from landfills, sewage	Major methane source
Industry	Carbondioxide and fluorinated gases	Increasing with industrialization
Transportation	carbondioxide from combustion engines	Rapidly growing sector

Source: Nunes (2023), Werku et al., (2025)

2.3 Implications for Climate Policy and Mitigation

To limit the effects of global warming, climate strategies must prioritize both the reduction of carbondioxide and mitigation of gases such as methane and nitrous oxide which have high impacts on the environment (Omotoso and Omotayo 2024). The use of renewable energy systems such as biogas offers a low-carbon alternative to the use of fossil fuels while simultaneously addressing the emission of methane from organic waste streams (Omotosho et al., 2023). With this dual capability positions of biogas of being at the intersection of transmission of energy, management of wastes and climate mitigation planning. As nations work towards Net-Zero emission goals, sustainable development agendas and technologies that recover energy by reducing atmospheric methane concentration are crucial (Mirzabaev et al., 2023).

3.0 BIOGAS PRODUCTION TECHNOLOGY

3.1 Anaerobic Digestion Process

This is a microbiological process that involves the decomposition of organic materials in the absence of oxygen with biogas the resultant output. The biogas output is majorly composed of methane (CH₄) and carbon dioxide (CO₂) (Handa and Rajamani 2023). The digestion process can occur naturally in wetland and marshy areas, and the digestive tracts of ruminants, whereas the process is controlled within digesters engineered to optimize the production of gas (Harirchi et al., 2022). Anaerobic digestion a biogas technology that is central and can provide an environmentally friendly method of renewable energy production from agricultural, municipal, industrial, and domestic organic wastes (Ngabala and Emmanuel, 2024). There are four

main biochemical stages in anaerobic digestion and each stage has microbial communities that is specialized and their interactions impacts on the production of biogas. The stages are hydrolysis, acidogenesis, acetogenesis and methanogenesis.

3.1.1 Hydrolysis

It is the first step in the anaerobic digestion process and often rate-limiting. At this stage, there is breakdown of complex organic macromolecules such as proteins, lipids and carbohydrates into smaller and compounds that are more soluble (Alengebawiy et al., 2024). At this stage, the hydrolytic bacteria secrete cellulases, lipases and proteases which are enzymes that facilitate breakdown of complex polymers into simple sugars, fatty and amino acids (Li et al., 2024). When this is done, the availability of substrate for other bacterial groups in other anaerobic digestion stages are improved. The process of hydrolysis must be effective as materials that are poorly hydrolyzed cannot be converted into methane (Siddiquey et al., 2025).

3.1.2 Acidogenesis

It is the next stage after hydrolysis and involves converting soluble compounds into different intermediate products. Some of these major products are alcohols, ammonia, carbon dioxide, volatile fatty acids and other organic compounds (Li et al., 2024). A major bacterium with active role in this stage is acidogenic or fermentative bacteria which consumes sugars and amino acids rapidly and promotes the buildup of volatile fatty acids which can reduce the pH (Ramos-Suarez et al., 2021; Sanchez-Ledesma et al., 2023).

3.1.3 Acetogenesis

It is the next stage and involves the conversion of acidogenesis produced alcohols and volatile fatty acids into carbon dioxide and acetate hydrogen. The microbial agents in this stage are the acetogenic or syntrophic bacteria which can function under conditions of low-hydrogen, and also depends on methanogens that are hydrogen consuming for maintenance of optimal partial pressure of hydrogen. Acetate produces about 60 – 70% of methane in most anaerobic digesters and very efficient in methane production (Cao et al., 2025).

3.1.4 Methanogenesis

It is the last stage in anaerobic digestion process and also the most critical as methanogenic archaea converts hydrogen, acetate and carbon dioxide into methane. This stage is favoured by conditions that are strictly anaerobic, pH should be between 6.8 – 7.2, temperature range should be mesophilic (35–40°C) or thermophilic (50–55°C) and stability in rates of organic loading (Marić et al. 2024). This stage is significant in mitigation of climate as it stabilizes organic wastes by producing methane. This can be used for production of energy

rather than emission to the atmosphere thereby contributing to the reduction of greenhouse gases (Un 2025). Biogas is composed of gases such as methane (50 – 75%), carbon dioxide (25 – 45%) and trace gases (1 – 5%) like hydrogen sulphide, nitrogen, hydrogen, oxygen ammonia. The residue is usually rich in organic fertilizer and can be used in place of synthetic fertilizers on crop farms thereby reducing the emission of nitrous oxide (Un, 2025).

3.2 Biogas Feedstock Sources

Biogas feedstocks are materials that are organic in nature and can be decomposed by anaerobic microorganisms to produce biogas and digestate which is a rich fertilizer. The feedstocks can vary in based on its origin, composition, biodegradability, and gas yield production (Un 2025).

3.2.1 Agricultural residues

These are by-products from crop production which can be residue from crops such as sorghum and maize stalks, rice straw, peels from yams and cassava peels, residues from agricultural processing such as sugarcane bagasse, wastes from fruit and vegetables and oilseed residues such as shells from groundnut and palm oil mill effluent (POME). These residues are abundant in farms and has high lignocellulose contents and must therefore be pretreated for optimal production of methane.

3.2.2 Livestock manure

It is one of the most common and reliable biogas feedstocks with examples such as pig manure, cow dung, sheep and goat manure and poultry droppings. It achieves a stable production of gas, although the moisture content is very high. It contributes essential microbes for digestion and can be co-digested with residue of crops for increased carbon Nitrogen ratio (Cao 2025).

3.2.3 Food and kitchen waste

They are wastes that are highly biodegradable and originates from homes, schools, restaurants, and food industries. Examples of such are the cooked food leftovers, foods that are spoilt, peels, offals from slaughterhouses, processing wastes from fish and meat (Worku et al., 2023). These feedstocks have high potential for methane production, easy decomposition attributes, rapid digestion process and requires careful handling to avoid infestation by pests and generation of offensive odour (Worku et al., 2023).

3.1.4 Industrial organic wastes

These are often organic effluents from agro-industrial processes. Examples are from brewery and dairy industry wastes, sludge from paper mills, starch mill

effluents and wastewater from slaughter houses (De Silva et al., 2023). They have high organic load and are good feedstocks for large-scale biodigesters. At times, dilution is required due to the high biochemical oxygen demand (Pandit et al., 2021; Abdel-Fatah 2023).

3.1.5 Sewage and municipal solid waste.

These are derived from urban environments and examples are wastes from markets, green wastes from parks, sewage sludge, and organic fraction of municipal solid wastes. It requires sorting and can expand the production potential of biogas in cities (Abdel-Fatah et al., 2023; Cao et al., 2025).

3.1.6 Energy crops

These are crops that are cultivated specifically to produce biogas. Examples of such crops are elephant grass, maize silage, alfalfa, sorghum and water hyacinth which is invasive but very useful in biogas production. There is usually high yield of biomass, supply is reliable and if not managed properly can compete with land for production of food (De Silva et al., 2023).

3.1.7 Aquatic Biomass

They are the fast-growing aquatic plants and algae with examples as water lettuce, hyacinth, algae and duckweed (Sayanathan et al., 2024). They do not compete with farmland and are very useful in treatment systems of wastewater (Zhou et al., 2023).

4.0 BIOGAS AS A CLIMATE CHANGE MITIGATION TOOL

4.1 Methane Capture and Utilization

Naturally, organic wastes can decompose without anaerobic digestion thereby releasing methane to the atmosphere. The technology can capture and combust methane, thereby converting it into carbon dioxide with an intensity that is significantly lower (Symeon et al., 2025). When treatment is not controlled, organic wastes can undergo anaerobic decomposition thereby resulting into the emission of methane uncontrollably. Methane is a greenhouse gas with a warming potential of 28-34 times more than carbon dioxide; making it a major contributor to climate forcing in landfills, open dumps, wastewater lagoons and livestock waste systems that is unmanaged (Zaks et al., 2011).

The biogas technology provides a pathway towards effective climate mitigation by capturing methane at its source and prevents its release directly into the atmosphere. Biodegradable materials are usually broken down through anaerobic digestion in sealed environments to produce a stream of biogas containing 50 – 70% methane. When the methane is combusted for

heat and electricity generation or upgrade to biomethane, it is transformed into carbon dioxide (Symeon et al., 2025).

4.1.1 Methane Reduction Pathway

There are three complementary mechanisms that dictate the greenhouse gas reduction potential of biogas systems; they are methane avoided, methane used as fuel and digestate nutrient reuse.

- **Methane avoided:** it involves the process of capturing methane that would have been emitted when wastes are decomposed uncontrollably (Savanathan et al., 2024).
- **Methane used as fuel:** it is a process of substituting fossil fuels such as diesel, kerosene, LPG with biomethane that is upgraded or with biogas. This reduces the life-cycle carbon dioxide emissions and displacing energy sources that are from non-renewable sources (Un 2025).
- **Digestate Nutrient Reuse:** it involves the use of digestate as an organic fertilizer thereby reducing the dependence on synthetic fertilizers, as their production is energy-intensive and is associated with significant emission of carbon dioxide and nitrous oxide (Siddikey et al. 2025)

With the combination of these pathways, the biogas systems can successfully achieve a reduction of approximately 50–90% greenhouse gas (GHG) emission, which is a function of the type of feedstock, design of biogas system, energy substitution efficiency, and management practices of digestate (Zhou et al., 2023; Yuan et al., 2024).

4.2 Energy Substitution and Carbon Offset

The production of biogas plays a significant role in climate mitigation by substituting fossil-based energy sources and generating measurable carbon offsets. Its versatility allows it to replace multiple high-emission fuels across different sectors of the economy. The use of biogas displaces the use of fossil fuel for production of heat, generation of electricity, transportation, cooking and industrial boilers. When biogas is purified to about 95%, it becomes biomethane and it is very comparable with gas from natural sources.

4.2.1 Fossil Fuels Displaced by Biogas

The use of biogas can effectively substitute fuels that are conventional in nature and used in the following applications:

- **Electricity Generation:** It can be used as alternatives to diesel, coal based and natural gases and used in internal combustion engines,

gas turbines, and combined heat and power (CHP) systems (Nunes 2023).

- **Heat Production:** It is used to provide thermal energy for water heating, operations of boiler, and other industrial processes. This approach displaces the use of firewood, diesel, LPG, and heavy fuel oil.
- **Transportation:** When biogas is purified, it can be upgraded to biomethane or compressed as Bio-CNG. It can be used as a clean transport fuel, thereby replacing petrol and diesel (Omotoso and Omotayo 2024).
- **Cooking and Industrial Boilers:** It is a renewable alternative to kerosene, LPG, and fuelwood for household cooking and commercial or industrial thermal applications (Symeon et al., 2025).'

4.2.2 Biomethane for Higher-Value Energy Use

Biomethane can be injected into natural gas grids, used in CNG vehicles, converted to liquefied biomethane, or applied in high-efficiency industrial systems. This enhances both the energy value and the carbon offset potential of biogas, thereby resulting into a deeper integration into national energy systems (Pavičić et al., 2022). A cm³ of biogas has an energy quantity equivalent of 0.65 litres of petrol, 3.5kg of firewood and 2 kWh of electricity. The replacement of fossil energy on a large scale reduces the emission of carbon dioxide and strengthens the security of energy.

4.3 Energy Substitution and Carbon Offset

Biogas has the capacity as an energy source to displace the conventional fossil fuels across multiple sectors (Nunes 2023, Un 2025). When diesel, petrol, natural gas, kerosene, and liquefied petroleum gas (LPG) are substituted, biogas systems can create substantial carbon offsets that contribute directly to climate change mitigation. Some of the key areas where fossil fuels can be substituted are:

- **Electricity Generation** - Biogas can be used in gas engines or microturbines, to generate electricity. This approach replaces the use of grid electricity which is often produced from sources such as diesel generators, coal, or natural gas which are fossil-based.
- **Heat Production** - The direct combustion of biogas provides thermal energy for small-scale cooking, water heating, and large-scale industrial processes. This process displaces fuelwood, LPG, diesel, and coal thereby reducing CO₂ emissions and alleviating pressure on forest resources.
- **Transportation Fuel** -When upgraded to biomethane or compressed to Bio-CNG, purified biogas can be used as a clean transport fuel for

vehicles, motorcycles, tricycles, and fleet systems. This can reduce the dependence on petrol and diesel and reduce the emission of particulate matter in urban centers.

- **Cooking and Industrial Boilers** - Biogas provides a clean alternative to kerosene, LPG, and firewood for households and commercial facilities. In industrial boilers, it offsets heavy fuel oil and natural gas consumption.

5.0 GLOBAL STATUS OF BIOGAS ADOPTION

Biogas adoption has expanded across continents as countries seek sustainable alternatives to fossil fuels, improve waste management, and reduce greenhouse gas emissions (Sidi Habib and Torii 2024). Global uptake varies widely by region, shaped by differences in policy support, economic capacity, technological advancement, and local resource availability. While Europe leads in large-scale industrial biogas systems, Asia dominates in household digesters, and Africa shows growing but still emerging potential (Abanades et al., 2021; Tagne et al., 2021; Holewa-Rataj et al., 2025).

5.1. Europe

The continent remains the global leader in biogas technology deployment and policy-driven expansion. The key features include the over 18,000 operational biogas plants which can contribute significantly to the production of renewable energy. They have a robust policy framework which includes feed-in tariffs and guaranteed grid access, taxes on carbon incentives and subsidies for anaerobic digestion (AD) technologies. They have a widespread integration of biomethane into national gas grids, especially in Germany, Denmark, France, Italy, and the Netherlands. The transition toward green gas corridors and decarbonized heating systems is very active with a strong emphasis on circular economy principles, thereby using agricultural residues, manure, sewage sludge, and food waste for biomass generation. The leadership of Europe is driven by climate commitments long-term, regulatory enforcement that is strong, and advanced technology ecosystems (Handa and Rajamani 2023).

5.2 China and India

Both countries are global leaders in small- to medium-scale biogas systems, especially for rural households and farm communities. In the rural provinces, China hosts millions of household biogas digesters, and have a strong government support historically through the National Biogas Program. There is an increased shift from household digesters to large-scale agricultural and municipal biogas plants. The country focuses on manure-based systems for improving sanitary conditions and reducing open waste dumping, and the emerging interest in biomethane production for transport and industrial fuel (Dwivedi et al., 2022).

India is the home to vast numbers of domestic digesters through programs like the National Biogas and Manure Management Programme (NBMMMP). They lay emphasis on rural energy access, clean cooking, and improved farm productivity and have a strong focus on gobar gas (cow dung-based digesters) and agricultural waste systems.

5.3 Africa

The adoption of biogas Africa is increasing but remains underdeveloped compared to other regions. They are faced with challenges such as the high upfront capital costs that is associated with installation of biodigester. There are limited technical knowledge among local artisans and users, weak policy incentives, with few countries offering subsidies or feed-in tariffs, poor waste-collection infrastructure, especially in urban and peri-urban areas (Harirchi et al., 2022)

6.0 CONCLUSIONS

The production of biogas represents a solution towards circular economy by addressing climate change, renewable energy demand, and management of wastes. It captures methane that would otherwise escape into the atmosphere, substitutes fossil fuels, reduces nitrous oxide emissions through organic fertilizer use, and enhances soil carbon storage. Although, with the financial, institutional and technical challenges, the advancements in upgrading biomethane, digital monitoring, and policy frameworks have placed the production of biogas as a major contributor to global GHG reduction pathways.

Conflicting Interests

The authors state that no conflict of interest exists.

Authors' contributions

All authors were involved in the conceptualization, arrangement, the proofreading and approved the manuscript before submission.

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