Compressed Biogas Plant: Overview and its Application

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ABSTRACT

This paper presents a comprehensive review of compressed biogas (CBG) technology, focusing on its production processes, plant components, and applications as an alternative automotive fuel. CBG is produced through anaerobic decomposition of organic waste materials including agricultural residues, municipal solid waste, and industrial organic waste. The study examines two primary digestion methods: wet digestion (≤10% dry matter) and dry digestion (≥10% dry matter), comparing their operational characteristics and efficiency parameters. Key findings indicate that CBG can reduce greenhouse gas emissions by up to 90% compared to conventional diesel fuel when used in natural gas vehicles. The paper analyses major plant components including feedstock conditioning systems, anaerobic digesters, biogas treatment units, and compression systems. Government initiatives, particularly India's SATAT (Sustainable Alternative Towards Affordable Transportation) scheme, are driving CBG adoption with targets of establishing 5,000 CBG plants by 2025. However, technological limitations including temperature dependency, purification challenges, and high capital costs remain significant barriers. This review synthesizes current literature to identify research gaps and future development opportunities in CBG technology for sustainable transportation fuel applications.

Keywords: Compressed biogas; anaerobic digestion; renewable fuel; biogas upgrading; SATAT scheme; sustainable transportation

INTRODUCTION

Compressed Biogas, commonly referred to as CBG, is derived from diverse organic waste sources including agricultural residues, sugarcane press mud, and municipal solid waste through the process of anaerobic decomposition. This renewable fuel can be effectively utilized as an automotive energy source, offering significant environmental advantages over conventional fossil fuels.

Figure 1: Biogas Plant situated in India. [10]

India's robust economic expansion and escalating energy demands necessitate substantial increases in energy production capacity for the forthcoming years.

According to the Ministry of Petroleum and Natural Gas (MoP&NG), India's proven crude oil reserves are estimated at 763 million metric tonnes (MMT), while natural gas reserves stand at 1,488 billion cubic metres (BCM) [4]. Data from the World Bank indicates that India imports approximately 77% of its crude oil requirements and 50% of its natural gas consumption. To mitigate this heavy dependency on energy imports, the government has established the strategic objective of reducing import reliance by a minimum of 10% by 2025. Additionally, the target for natural gas contribution to India's overall energy mix has been substantially increased from the current 6.5% to an ambitious 15%, moving closer to the global average of 23.5% [22].

Biogas represents a naturally occurring renewable energy source produced through the metabolic activities of anaerobic bacteria during the decomposition of organic materials, and it serves as a versatile medium for energy generation [4]. Compared to conventional fossil fuels such as natural gas, biogas emerges as an environmentally sustainable energy alternative that is generated through natural anaerobic digestion processes. This eco-friendly technology offers numerous environmental and economic benefits. Biogas technology enables the efficient utilization of animal waste from agricultural production systems as well as municipal solid waste generated through rapid urbanization processes [9]. The conversion of organic waste materials into biogas significantly reduces the emission of methane, a potent greenhouse gas, by efficiently combusting the methane to produce carbon dioxide. Since carbon dioxide exhibits approximately 21 times lower heat-trapping efficiency in the atmosphere compared to methane, the combustion of biogas substantially reduces overall greenhouse gas emissions. Traditional manure storage systems are typically associated with unpleasant odors, pest infestations, and potential disease transmission. The implementation of biogas generation systems on agricultural farms can effectively mitigate these environmental and health concerns.

The production of biogas can be achieved utilizing both animal and plant-based organic waste materials. Anaerobic digesters process organic waste by creating a liquid suspension or slurry through the addition of water to facilitate bacterial decomposition. For optimal bacterial digestion to occur, anaerobic digesters must incorporate several essential components, including heat exchangers and feedstock supply tanks. Rural communities can implement small-scale digesters with capacities up to 757 litres (200 gallons) to generate cooking fuel or electrical power for household consumption. The utilization of domestic-scale digesters as renewable energy sources has gained widespread adoption in numerous developing nations, particularly in China and various African countries. Large-scale digesters are specifically designed to process liquid or sludge waste generated from agricultural operations. A diverse range of agricultural digester configurations can be employed for processing agricultural waste materials, including covered lagoons, complete mix digestion systems, plug-flow digestion units, and specialized dairy manure digesters [9]. The bacterial decomposition of organic materials into biogas can only occur effectively when digesters maintain optimal temperatures of 35°C (95°F) or higher. Under these conditions, digesters can produce between 200–400 cubic metres of biogas (7,000–14,000 cubic feet) per dry metric tonne of feedstock material, with biogas typically containing 50–75% methane content.

Various waste and biomass sources contribute to biogas production through anaerobic decomposition, including municipal solid waste, wastewater treatment plant sludge, agricultural residues, and livestock manure. The raw biogas undergoes purification processes to remove impurities and is subsequently compressed to produce Compressed Bio Gas (CBG). This refined CBG achieves methane (CH_4) concentrations exceeding 90% while being virtually free of hydrogen sulfide, carbon dioxide, and water vapor, making it suitable for direct utilization as a vehicle fuel [12].

LITERATURE REVIEW

The evolution of biogas technology research spans over three decades, with significant developments in technical, economic, and policy aspects. This comprehensive review synthesizes key findings from existing literature to highlight technological advancements, economic viability studies, and recent developments in compressed biogas applications.

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The foundational research by Ashok Kumar in 1990 demonstrated that biogas technology faced significant economic and social challenges during its early development phase [6]. Kumar's analysis revealed that biogas technology was economically non-viable at that time, primarily due to substantial social adjustment difficulties encountered during the transition from conventional to biogas-based systems. Crucially, Kumar highlighted a fundamental misconception that organic materials such as manure were merely waste products, when in reality they possessed inherent economic value as agricultural inputs. Building upon these early findings, Abbasi's comprehensive study in 1993 provided detailed engineering designs and cost analyses for four promising high-rate digester configurations [3]. This research established a systematic modeling approach that enabled benefit-cost ratio calculations based on specific operational parameters. Abbasi's work was particularly significant for its forward-looking perspective, addressing not only contemporary challenges but also projecting future technological developments and market conditions.

The mid-1990s marked a shift toward technical optimization of biogas systems. Tiwari et al. (1995) developed analytical expressions for determining optimal retention times in biogas plants of varying capacities [6]. Their research demonstrated that solar-assisted heating could significantly reduce retention periods, leading to improved operational efficiency. The mathematical models developed by Tiwari's team provided valuable tools for designing and testing solar-aided biogas installations, with parametric studies offering insights into optimal operational conditions.

The Government of India's comprehensive evaluation in 2002 examined successful rural biogas implementations, focusing on two exemplary models: the SUMUL Dairy community biogas facility in Bhintbudrak, Gujarat, and an NGO-managed individual biogas project in Maharashtra's south Konkan region [7]. These case studies provided practical evidence of biogas technology's viability in rural cooking applications and highlighted the importance of community-based approaches. Madlener's comparative analysis in 2006 introduced multi-criteria decision analysis (MCDA) and data envelopment analysis (DEA) methodologies for evaluating renewable energy installations across economic, environmental, and social dimensions, establishing important benchmarks for assessing biogas system performance and efficiency [6]. Research focus expanded significantly during 2009-2015 to include diverse organic waste sources. Sagagi's 2009 investigation demonstrated successful biogas production from food waste, with the additional benefit of generating high-quality organic fertilizer from both digested and undigested sludge [6]. The study revealed that cow dung-based slurries achieved the highest weekly biogas production rates, establishing important baseline parameters for feedstock comparison. Bhumesh Singh's 2011 research addressed the dual objectives of dairy effluent management and biogas generation, focusing on water pollution reduction while maximizing energy recovery [12]. Singh's process optimization considered critical parameters including temperature, pH, biochemical oxygen demand (BOD), and chemical oxygen demand (COD), leading to iterative improvements in system design and operation.

Recent research has focused on compressed biogas applications and large-scale implementation strategies. Jiang et al.'s (1989) early work on compressed biogas applications in dual-fuel engines provided foundational understanding for automotive applications [14], while Bajracharya et al. (2009) contributed significant insights into biogas purification and compression technologies for enhanced energy applications [1]. Modern economic feasibility studies, such as Tonrangklang et al.'s (2022) analysis of compressed biomethane applications in Thailand, have demonstrated improved financial viability through technological advances and supportive policy frameworks [21]. Similarly, Yadav and Sircar's (2022) comprehensive review of CBG integration into city gas distribution networks in India highlighted the technical and regulatory developments enabling large-scale deployment [22]. Kumar et al.'s (2019) assessment of CBG potential as a green energy source in India provided updated projections for national-scale implementation [16], while Kabeyi and Olanrewaju's (2022) research positioned biogas within the broader sustainable energy transition framework [15]. Minde et al.'s (2014) earlier work established biogas as a sustainable alternative for India's current energy needs, providing foundational understanding for subsequent policy development [17]. These contemporary studies reflect the maturation of biogas technology from experimental installations to commercially viable renewable energy systems.

The literature reveals several persistent challenges requiring continued research attention. Technological limitations identified include temperature dependency of biogas production, purification system efficiency, and

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long-term operational reliability [18]. Economic analyses consistently highlight high capital costs and extended payback periods as barriers to widespread adoption. Recent policy initiatives, particularly India's SATAT scheme, have created new research opportunities focusing on scale-up challenges, grid integration, and supply chain optimization [11]. However, limited research exists on implementation barriers, technology transfer mechanisms, and long-term sustainability assessment of large-scale CBG programs.

The evolution from individual biogas plants to integrated waste management and energy production systems represents a significant paradigm shift, with numerous Indian states now hosting operational biogas installations supported by evolving government policies and implementation frameworks. From 2011 to present, extensive research inputs have been conducted, leading to model evolution based on enhanced feasibility and viability assessments. Various new policies have been introduced and implemented by the government to support this technological advancement.

Advantages & Disadvantages

Table 1: Advantages [7]

S. No.	Advantage	Description
1.	Biogas is Eco-Friendly	Using biogas as a fuel is a great way to get both clean and sustainable energy. Natural gas produced by bio digestion does not pollute and really helps to minimise global warming emissions (i.e., reduces the greenhouse effect).
2.	Biogas Generation Reduces Soil and Water Pollution	In the end, another benefit from biogas production is that it may help to clean up polluted waterways. Anaerobic digestion also deactivates bacteria and parasites, making it a very efficient tool for minimising the spread of waterborne illnesses.
3.	Biogas Generation Produces Organic Fertilizer	Enriched organic digestate, a by-product of the biogas generating process, is an excellent addition to or replacement for chemical fertilisers.
4.	It’s A Simple and Low-Cost Technology That Encourages a Circular Economy	Biogas production is made possible by low-cost technologies. When utilised on a small scale, it is simple to put up and inexpensive to operate.”
5.	Healthy Cooking Alternative for Developing Areas	The collection of firewood by women and children is lessened because to the use of biogas generators. You will have extra time to cook and clean as a result of this. Using a gas stove instead of an open fire means that no one in the family will inhale smoke while cooking.

Table 2: Disadvantages [7]

S. No.	**Disadvantages**	**Description**
1.	Few Technological Advancements	Unfortunately, today's biogas production techniques are inefficient, which is a drawback. To yet, no new technology has been developed to make the procedure easier to use, more accessible, or less expensive for everyone to use.
2.	Contains Impurities	Impurities remain in biogas even after it had been refined and compressed. The metal components of the engine might rust if the created bio-fuel is put to use as a vehicle fuel.
3.	Effect of Temperature on Biogas Production	Biogas production is weather-dependent, just like other renewable energy sources (such as solar and wind). When it comes to digestion, bacteria prefer a temperature of 37°C. When operating in cold regions, digesters require additional heat energy to keep the flow of biogas consistent.
4.	Less Suitable for Dense Metropolitan Areas	Another downside of industrial biogas plants is that they only make sense in places where substantial volumes of raw materials (food waste, manure) are easily accessible.

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Biogas Plant Components

Table 3: Biogas Plant Components

S. No.	Component	Work
1.	**Site**	Several aspects need to be studied in the choice of a site: Dominant wind/Air dispersion Road access & Geotechnical Proximity to energy grids Contamination & Proximity of neighbours
2.	**Civil Work**	All of these things based on biogas plant's design determines the Civil Work.
3.	**Buildings**	Shelter for Civil Workers Garage for Trucks & Feedstock Place for Digesters Storage Area for Liquid & Gas Output
4.	**Reception**	Feedstock Storage Trucks Garage These should be properly built to avoid foul smell & for maintaining Hygiene
5.	**Feedstock Conditioning**	A variety of processing techniques are used here to prepare materials for use in digesters. It is possible to disinfect it using methods like these: Hydro-pulpers Separating hammermills Presses & Mills
6.	**Anaerobic Digestion**	The digesters are crucial components of biogas plants since it is in them that anaerobic bacteria decompose the feedstock and produce biogas and digestate
7.	**Digestate Treatment**	Separation: To separate the liquid portion from the solids, compress the digestate after it has been prepared. Composting: In order to stabilise or allow drying and purification of the digestate's solid component, a biogas plant may be fitted with a composting unit. Wastewater treatment: Before disposing of the digestate in the environment or into sewage, the liquid portion must typically be processed. In order to prevent odours from leaking into the environment, they must be regulated (through correct ventilation) and treated on site.
8.	**Biogas Handling**	Pipes, Flowmeters, Condensate traps, Storage & Flare
9.	**Biogas Treatment & Utilization**	Using this equipment is necessary to meet the criteria needed for its intended usage of biogas. Equipment that enables the use of biogas or biomethane (RNG) in the following manner: Boiler, CHP, Biogas upgrader & Compressor.

Construction & Working:

Wet Digestion

When the digester's contents can be pumped out, the procedure is classified as wet digestion. This signifies that the digested material has a dry matter consistency of no more than 10%. (90 percent water). Wet digesters come in a wide variety of configurations:

- “Complete mix or completely stirred tank reactor (CSTR)
- Plug-flow & Sludge bed reactors
- Up flow Anaerobic Sludge Blanket (UASB)
- Fixed film reactor & Floating films reactors”

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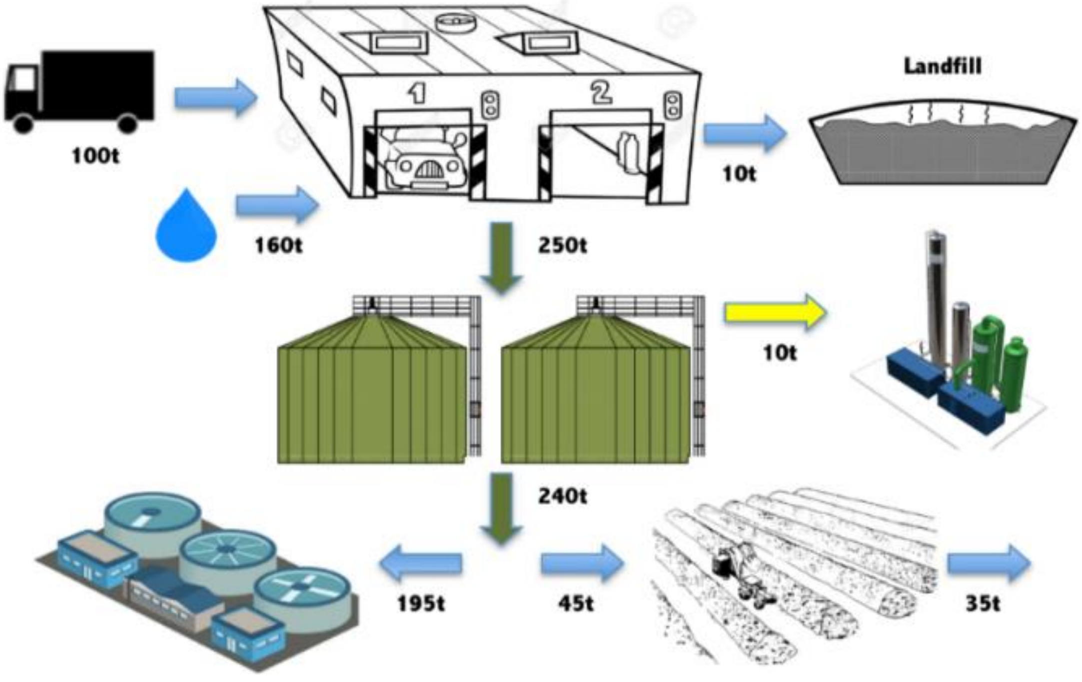

Figure 2: Process of Wet digestion [9]

A variety of feedstock conditions and commercial uses have led to the development of these process setups. The biogas facility takes 100 metric tonnes of municipal solid waste from residential sources segregated organically (SSO) for wet digestion (complete mix). If there are any contaminants in the completed product, pre-treatment of this feedstock is necessary to remove them (plastics, metal, sands, etc.). A total of 10 tonnes of hazardous waste will be collected and disposed of, most likely in landfills.

Dry Digestion

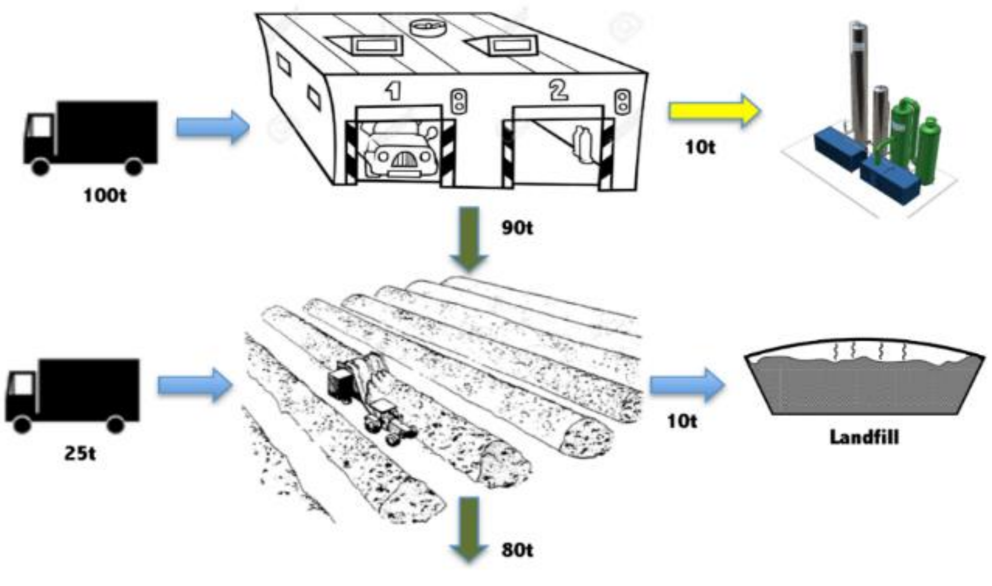

Figure 3: Mass balance of Dry Digestion [9]

It is called dry digestion when the digester's contents cannot be pumped out. As a result, the material in the digester is around 10 percent dry matter or higher in consistency. Various dry digester layouts are available on the market:

- Continuous vertical
- Continuous horizontal
- Batch (Garages)

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These set-ups have been created to maximise the process's efficiency under a variety of feedstock and market situations. In a normal dry digestion process, the mass balance is as shown below.

When 100 tonnes of municipal solid waste are sent to a biogas plant via dry digestion, it is processed into energy (garage style). Because of this, there is no need to pre-treat the feedstock (plastics, metal, sands, etc.). Biogas will be produced in the digesters by bacterial consumption of the feedstock's volatile solids. Digestion will produce about 10 tonnes of gas per day. Approximately 90 tonnes will be made up of the solid digestate. [12] As a result, there will be a greater volume of digestate excreted compared to the amount of entering materials. Adding a bulking agent before digestion can help keep the waste from digestion from dissolving. The material may come out as a thick liquid in some continuous "dry" digesters. It is difficult to recycle this liquid on land since it is still contaminated with (plastics, metals, stones and sands, etc.) [5] Different successful Business projects for biogas are CBG project at Varanasi, Uttar Pradesh; . Hisar, Haryana; Haridwar BioCNG project, Uttarakhand; Bharat Biogas Energy Limited, Umreth, Gujarat; Zakariyapura cluster model, Anand Gujarat, A pilot project by NDDB; Banaskantha BioCNG plant, Banaskantha, Gujarat.

Application of Biogas or Natural Gas as A Fuel

Raw biogas cannot be directly utilized in compressed natural gas vehicles due to corrosive components that compromise high-pressure cylinder integrity [2]. Critical impurities including hydrogen sulfide (H2S), carbon dioxide (CO2), and water vapor (H2O) must be removed before liquefaction to prevent corrosion and ice formation [3]. Biogas requires conversion into renewable natural gas (RNG) or biomethane through purification processes, enabling direct substitution for conventional natural gas in automotive applications [12]. Natural gas vehicle (NGV) refueling stations are typically located near biogas facilities that inject upgraded biomethane into existing pipeline networks [11]. However, consistent supply remains challenging as biogas plants must maintain production rates aligned with grid demand cycles.

Environmental benefits are substantial compared to conventional fuels. Natural gas vehicles demonstrate 25% reduction in greenhouse gas emissions compared to diesel equivalents, while renewable natural gas applications can achieve over 90% reduction in transportation-related emissions [5]. CBG can be produced from diverse sources including agricultural residues, municipal waste, sugarcane press mud, livestock manure, spoiled produce, dairy waste, poultry litter, and industrial organic waste [20, 10]. Future development envisions integration of CBG networks with city gas distribution (CGD) systems, enhancing supply to residential and commercial consumers [2]. Bank of Baroda provides specialized lending schemes for CBG project development and implementation [2].

Government Support Schemes & Future Potential –

The 2018 National Policy on Biofuels prioritizes compressed biogas as a critical component of advanced biofuel development [11]. The GOBAR-DHAN (Galvanizing Organic Bio-Agro Resources) initiative transforms livestock waste and agricultural residues into CBG and organic compost [19]. The 2018-19 framework projects over 700 CBG projects nationwide.

The Swachh Bharat Mission-Gramin (SBM-G) supports rural waste management through its Solid and Liquid Waste Management component [7]. The Ministry of New and Renewable Energy (MNRE) offers Central Financial Assistance up to Rs. 4 crores per project, with maximum support of Rs. 10 crores for installations producing 4,800 kg CBG daily [8]. The Reserve Bank of India designated CBG projects as priority sector lending, while State Bank of India developed comprehensive financing strategies for CBG initiatives [2]. The Ministry of Agriculture included "Fermented Organic Manure" in the Fertilizer Control Order, encouraging organic farming and creating additional revenue from CBG by-products [13]. State-level committees in Haryana, Punjab, and Uttar Pradesh oversee SATAT scheme implementation and monitoring [12]. Production sources encompass sewage treatment waste, livestock manure, agricultural by-products, and industrial organic waste from effluent treatment plants [8].

Table 4: Comparison between Wet & Dry Digestion"

"Process Mode	Dry Digestion	Wet Digestion
Total Moisture Content	Low 55%-75%	High 85%-98%
Total Solids Content	High 25%-45%	Low 2%-15%
Reactor Volume	Minimized	Increased
Conveyance Technique	Expensive	Simple
Agitation	Difficult	Easy
Scamming	Little Risk	High Risk
Short Circuit Flow	Little Risk	High Risk
Solid-Liquid Separation	Simple	Expensive
Variety Of Waste Components	Small	Great

The planned integration of CBG networks with city gas distribution systems will enhance supply reliability and accessibility [8]. This supports India's vision of Sasya-Syamala Bharat (Green and Prosperous India) through sustainable energy development [11]. Companies like SVM Infraestate Pvt Ltd demonstrate private sector commitment through their "Swachh Vande Mission," installing CBG plants nationwide to achieve Clean and Green India objectives.

CONCLUSION

Compressed biogas (CBG) represents a transformative renewable energy technology that addresses multiple challenges simultaneously: waste management, energy security, and environmental sustainability. Derived from diverse organic waste sources including agricultural residues, sugarcane press mud, and municipal solid waste through anaerobic decomposition, CBG emerges as a viable alternative automotive fuel with significant environmental advantages over conventional fossil fuels [12].

India's robust economic expansion and escalating energy demands necessitate innovative solutions to reduce import dependency and enhance energy security. The evolution of biogas technology since the 1990s demonstrates remarkable progress from economically non-viable experimental systems to commercially feasible renewable energy installations [6]. Contemporary CBG technology offers substantial environmental benefits, including reduced soil and water pollution, greenhouse gas emission mitigation, and the production of high-quality organic fertilizer as a valuable by-product [9].

The technology's accessibility and cost-effectiveness make it particularly suitable for promoting circular economy principles while providing sustainable cooking alternatives for rural communities in developing regions [17]. However, several technical challenges persist, including temperature-dependent biogas production rates, purification complexities, and limited technological advancements in digester efficiency [18]. Additionally, raw biogas contains impurities that require comprehensive treatment before utilization as a vehicle fuel.

This comprehensive review has examined two primary production methodologies: wet digestion processes (≤10% dry matter content) enabling pumpable digester contents, and dry digestion systems (≥10% dry matter content) requiring mechanical handling approaches [7]. Each methodology offers distinct advantages and limitations depending on feedstock characteristics and operational requirements.

A critical finding of this analysis is that raw biogas cannot be directly utilized in compressed natural gas vehicles due to its corrosive constituents, which pose significant threats to high-pressure cylinder integrity [14]. The purification process must effectively remove hydrogen sulfide, carbon dioxide, and water vapor to prevent equipment damage and ensure optimal performance. This purification requirement represents both a technological challenge and an opportunity for innovation in CBG processing systems.

The potential for transforming waste materials into valuable energy resources presents unprecedented opportunities for sustainable development. Any quantity of organic biomass can theoretically be converted into biogas and bio-manure, offering pathways toward enhanced energy self-sufficiency while simultaneously addressing climate change mitigation objectives [15]. This dual benefit aligns perfectly with India's national goals of achieving energy independence while promoting environmental sustainability.

Government initiatives, particularly the SATAT (Sustainable Alternative Towards Affordable Transportation) scheme, demonstrate strong policy support for CBG development, targeting the establishment of 5,000 CBG plants with significant rural employment and income generation potential [11]. However, successful implementation requires continued research focus on technological optimization, economic viability enhancement, and supply chain development.

Future research directions should prioritize advanced purification technologies, temperature-independent production systems, and integrated waste management approaches that maximize both energy recovery and environmental benefits [21]. The integration of CBG into existing city gas distribution networks presents additional opportunities for scale-up and market penetration [22].

The vision of converting today's waste streams into tomorrow's energy resources is rapidly becoming reality through continued technological advancement and supportive policy frameworks. CBG technology offers a practical pathway toward India's ambitious goals of achieving Sasya-Syamala Bharat (Green and Prosperous India), contributing to both energy security and environmental sustainability objectives. As this technology matures and scales, it promises to play an increasingly vital role in India's renewable energy transition and sustainable development strategy.

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