Global Methane Initiative

Methane Mitigation: Lessons Learned from India's Compressed Biogas (Renewable Natural Gas) Projects

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List of Abbreviations

AD	Anaerobic Digester
BIS	Bureau of Indian Standards
C:N	Carbon-to-Nitrogen (ratio)
CBG	Compressed Biogas
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CSTR	Continuous Stirred Tank Reactor
EPA	U.S. Environmental Protection Agency
GMI	Global Methane Initiative
GHG	Green House Gases
GWP	Global Warming Potential
IOCL	Indian Oil Corporation Limited
IS	Indian Standard
LNG	Liquefied natural gas
MMT	Million metric tons
$MMTCO_2e$	Million metric tons of carbon dioxide equivalent
MST	Membrane separation technology
NDCs	Nationally Determined Contributions
NGO	Non-governmental organization
PPP	Public-Private Partnership
PSA	Pressure Swing Adsorption
SATAT	Sustainable Alternative Towards Affordable Transportation
TERI	The Energy and Resources Institute
VPSA	Vacuum Pressure Swing Adsorption
VS	Volatile solids

Executive Summary

This report presents the results of study analyzing a subset of India's compressed biogas (CBG) sector focusing on the potential role for this sector to create a market for a renewable energy resource while mitigating a significant source of methane emissions in India. The CBG (or renewable natural gas) sector encompasses a chain of interconnected activities including biogas production, purification, and compression to create a low-carbon energy option for diverse use cases such as transportation, power generation and heating. Methane, a potent short-lived greenhouse gas (GHG) with more than 28 times the global warming potential of carbon dioxide, plays a significant role in strategies for global GHG emission reductions.

India, a founding member of the Global Methane Initiative (GMI), has committed to expanding its CBG industry to improve the management of agricultural, industrial, and municipal waste streams. Expansion of the industry will reduce methane emissions, generate more domestic renewable energy, and address environmental and energy security goals. This focus is reflected in its national programs such as the Sustainable Alternative Towards Affordable Transportation (SATAT), which aims to establish 5000 CBG plants with an annual production capacity of 15 million metric tons (MMT) by 2030. The expansion is expected to produce about 15,000 metric tons of CBG per day, displacing up to 14,000 metric tons of fossil-based natural gas every day and mitigating an estimated 20 MMT of carbon dioxide equivalent ($MMTCO_2e$) in methane emissions annually. As of December 2024, India has approximately 115 operational CBG plants[1]. Four key feedstock categories such as agricultural waste, livestock waste, municipal solid waste, and press mud contribute to an estimated CBG potential of 40-60 MMT. However, significant biogas potential is lost due to practices such as burning of agricultural residues and limited segregation of municipal solid wastes[2].

India generates about 3 MMT of cow dung daily, presenting a significant opportunity to use this feedstock for generating new revenue streams through CBG production. If untreated, the cow dung would release methane into the atmosphere. Through anaerobic digestion, this quantity of cow dung can produce about 180 million cubic meters (m^3) of biogas per day and emits about 144 million m^3 of methane per day, which is equivalent to 2.70 MMT of CO_2e per day. The strategic management of feedstocks has the potential to play an important role in effectively reducing methane emissions using otherwise-emitted methane as an important energy resource.

This study of CBG facilities in India, conducted by the US Environmental Protection Agency (EPA) in collaboration with The Energy and Resources Institute (TERI) in support of GMI, evaluated 11 CBG facilities across northern India to identify ways to overcome operational challenges as well as

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[1] Down to Earth (2024). With no transparency on CBG production data, purpose of GOBARdhan portal remains unserved. https://www.downtoearth.org.in/energy/with-no-transparency-on-cbg-production-data-purpose-of-gobardhan-portal-remains-unserved

[2] IEA Bioenergy (2023). Enablers and Challenges- Indian Compressed Biogas (CBG) industry. https://task37.ieabioenergy.com/wp-content/uploads/sites/32/2023/05/Knowledge-Paper_Indian-CBG-Industry_IFGE_EAC_April-2023_18042023-1.pdf

opportunities to reduce methane emissions. The sites in northern India were chosen for this study due to its representative mix of agricultural, industrial, and municipal waste sources which are optimal feedstocks for CBG production. Additionally, the region's varied climate ranging from temperate to arid, supports year-round feedstock availability, making it a significant area for CBG expansion in India. The findings of the study provide actionable recommendations to overcome barriers and increase potential methane mitigation from the CBG sector. The primary challenges faced by the CBG facilities evaluated in this study are as follow:

1. Feedstock management
2. Inefficient purification systems and equipment
3. Staffing shortages and inadequate training
4. End-product management and market alignment
5. Regulatory and financial barriers

Feedstock management is hindered by inconsistent supply, price volatility, and quality issues. Addressing these challenges to secure a reliable supply chain, ensure optimal operation of the CBG facilities and therefore maximizing methane mitigation requires standardized agreements with feedstock suppliers, investment in adequate storage facilities, and establishment of quality control protocols.

The CBG facilities included in this study are also affected by **inefficiencies in purification systems and equipment** due to inappropriate technology and lack of real-time monitoring systems. Recommendations to improve CBG operations that would lead to more efficient operations and greater methane mitigation include thorough research in selecting technologies, adopting efficient monitoring systems, and adhering to maintenance standards to maximize methane capture. Additionally, **staffing shortages and inadequate training** impede operations, necessitating capacity-building programs and a culture of knowledge sharing to ensure workforce resilience and in turn more effective operations and methane reductions.

Ineffective **end-product management and market alignment** are also important barriers to effective operation and methane mitigation at CBG facilities. Some of the CBG plants studied incurred significant financial losses due to mismatched biogas production volumes and purchasing commitments of the buyer along with insufficient storage infrastructure. Underutilization of digestate as a potential value-added product constrained revenue diversification opportunity. The proposed mechanisms to address these challenges include conducting thorough market research, investing in storage solutions, and developing digestate-based value-added products for diversifying revenue streams.

Regulatory and financial barriers, including delays in permitting and limited access to financing, also impede the growth of CBG sector in India and limit methane mitigation. Several of the plants included in this study encountered challenges in obtaining necessary permits and securing financing due to administrative inefficiencies and limited understanding of the CBG initiatives offered by the financial sector. Recommendations include streamlining, expediting the permitting process with clear timelines, enhancing the capacity building programs for local authorities, providing knowledge toolkits for financial institutions to address administrative inefficiencies and lack of awareness about CBG projects and introducing insurance mechanisms to mitigate the perceived risk associated with investments.

The CBG sector in India offers a scalable and effective pathway for methane mitigation, transforming a potent GHG into a valuable clean energy resource. By addressing these challenges through effective management, enabling policies and investments, the sector can significantly reduce methane emissions while advancing energy security and sustainable development. This report provides analysis, insights, and actionable strategies for government agencies, project developers, non-governmental organizations, and other stakeholders to leverage the CBG sector's potential in methane mitigation while contributing to international climate action efforts.

1. Introduction

Methane, a potent greenhouse gas (GHG) with a global warming potential (GWP) 28 times greater than carbon dioxide on a ton-for-ton basis over a 100-year period, represents a critical challenge in global mitigation strategies. The agriculture, industrial, and solid waste sectors are the major contributors to global methane emissions. These sectors present both challenges and opportunities for methane mitigation. With appropriate technologies, the methane emissions from these sectors can be mitigated and harnessed as a valuable clean energy resource.

India has emerged as a global leader in mitigating methane emissions through compressed biogas (CBG) production. Using anaerobic digestion to process organic waste from agricultural and municipal solid waste (MSW), India's CBG sector transforms waste streams into biogas, a renewable energy source that replaces fossil based natural gas while reducing methane emissions and contributing to cleaner energy goals. Methane purified from biogas is compressed to create CBG, which is a low-carbon alternative to conventional natural gas and is used in several sectors including as transportation fuel. CBG is also known as renewable natural gas, biomethane, and biogas-based compressed natural gas (bio-CNG). The term CBG is more commonly used in India and is therefore used in this report.

India has launched many national initiatives to incentivize CBG production, including the Sustainable Alternative Towards Affordable Transportation (SATAT) program. SATAT is a national initiative of the Indian Federal Ministry of Petroleum and Natural Gas in partnership with the state-owned oil companies to establish CBG plants. The SATAT initiative aims to establish 5,000 CBG plants by 2025, producing up to 15 MMT of biogas annually.[3] Currently, India has over 100 large-scale CBG facilities in operation, with over 600 units under development and an extensive network of more than 5 million small-scale biogas plants.[4] India is already a major liquefied natural gas (LNG) importer, and the demand for natural gas is expected to triple by 2030. In FY 2023-24, India imported 66.7 billion m^3 of natural gas, with LNG accounting for nearly 50 percent of imports, valued at 13.3 billion U.S dollars[2]. The ambitious SATAT initiative aims to reduce India's energy dependence by promoting the use of cleaner alternatives to fossil fuel-based natural gas, significantly contributing to methane mitigation and reduction of carbon emissions.

According to the 20th Livestock Census of India conducted in 2019, the total bovine population is about 300 million, with cattle accounting for 64 percent. The massive livestock population results in the daily generation of around 3 MMT of cow dung,[5] a resource with significant potential for biogas and CBG production. However, if the cattle manure is left unmanaged, the decomposition of this organic waste

[3] Press Information Bureau. (2020). Rupees 2 lakh crore to be invested for setting up 500 Compressed biogas in the country. https://pib.gov.in/Pressreleaseshare.aspx?PRID=1674428

[4] Koonampilli, K. (2024). *Policy and market briefing 2024: India.* World Biogas Association in association with Invest India. https://www.worldbiogasassociation.org/wp-content/uploads/2024/10/WBA-India-Policy-and-Market-Briefing-2024.pdf

[5] Niti Aayog, Government of India. (2023). Production and promotion of organic and biofertilizers with special focus on improving economic viability of gaushalas. The Taskforce Report. https://www.niti.gov.in/sites/default/files/2023-03/Gaushala-report-2_14032023.pdf

releases substantial quantities of methane into the atmosphere. Through anaerobic digestion, this cow dung can produce an estimated 180 million m^3 of biogas per day.[6] Capturing this methane would mitigate about 144 million m^3 of methane emissions daily. This amount is equivalent to 2.70 MMT of CO_2e/day highlighting its critical role in addressing methane emissions.[7]

India has set ambitious targets through its Nationally Determined Contributions (NDCs) to reduce GHG emissions and enhance renewable energy capacity. The NDC's aim to reduce emissions intensity of Gross Domestic Product by 45 percent from 2005 levels by 2030 and achieve approximately 50 percent cumulative electric power installed capacity from non-fossil fuel-based energy resources by the same year.[8] Furthermore, India plans to implement mandatory blending of CBG with natural gas. Starting in April 2025, a 1 percent blending mandate will be introduced. The mandated percentage will progressively increase over time to reduce reliance on gas imports and promote use of indigenous feedstock thereby contributing to methane emission reductions.[9] This mandate underscores India's commitment to integrating methane emission reduction strategies with its broader climate action framework, leveraging the CBG sector's potential to achieve NDC targets.

To assess the CBG sector's role in methane mitigation, the U.S. Environmental Protection Agency (EPA) in collaboration with The Energy and Resources Institute (TERI) and in support of the Global Methane Initiative (GMI), conducted a study. The study involved 11 CBG plants across five states in northern India, including seven active facilities and four facilities that have ceased operations. The study identified economic, operational and regulatory barriers that affect the ability of CBG-based methane mitigation projects to live up to their environmental potential. Northern India was chosen for this study due to its representative mix of agricultural, industrial, and municipal waste sources that are optimal feedstocks for CBG production. The region's varied climate, from temperate to arid, supports year-round feedstock availability, making it a significant area for CBG expansion in India. TERI conducted site visits and interviews to gain insights about the challenges and successes of CBG production and EPA developed recommendations to foster greater adoption and scaling of methane mitigation strategies.

The economic viability of CBG plants is critical for scaling methane mitigation projects. Despite the environmental and energy security benefits, economic challenges such as feedstock cost variability, technical requirements, market demand for CBG and digestate end-use sales remain barriers to investment. This study highlights lessons learned from both active and inactive CBG plants, and their economic dynamics, providing valuable insights into overcoming operational challenges and scaling methane mitigation efforts in India. Through feedstock agreements, supply chain optimization, financing mechanisms, and technical standardization, the study identifies potential factors to support

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[6] Refer to Appendix C(1) for the calculation methodology
[7] Refer to Appendix C(2) for the calculation methodology

[8] Press Information Bureau. (2023). India achieves two targets of Nationally Determined Contribution well ahead of the time. https://pib.gov.in/PressReleaseIframePage.aspx?PRID= 1987752

[9] Press Information Bureau. (2023). Sustainable Aviation Fuel (SAF) using indigenous feedstock. https://pib.gov.in/ Press ReleaseIframePage.aspx?PRID=1925417

the growth of CBG sector while advancing methane mitigation objectives. In addition, the report provides recommendations for governments, project developers or operators, and non-governmental organizations (NGOs) to better support CBG production with methane mitigation programs and policies informed by real-world projects in other regions.

2. Methods

To assess the CBG sector's role in methane mitigation, TERI conducted site visits and comprehensive interviews with 11 CBG plants across northern India including seven active facilities and four plants that were no longer operational. The inclusion of non-operational facilities was integral to uncovering systemic challenges, such as feedstock supply disruptions, inadequate purification technologies, and regulatory and financial barriers. By analyzing these facilities, the study identified lessons to prevent similar failures in future projects, enhance risk mitigation, refine technical standards and strengthen policy frameworks, thereby supporting the scalability and resilience of the CBG sector to align with national methane mitigation goals.

The study team selected participating CBG plants to represent diverse system sizes, biogas end-uses, and feedstocks, all employing Continuous Stirred Tank Reactor (CSTR) anaerobic digesters and one of the four purification technologies: pressure swing adsorption (PSA), vacuum pressure swing adsorption (VPSA), water scrubbing and membrane separation technology (MST). CSTR systems are relevant in India due to their ability to handle diverse feedstocks and maintain consistent microbial activity through efficient mixing of feedstocks. They were included in the study because CSTR systems represent the most commonly used anaerobic digester type in India, offering insights into operational challenges and successes critical to advancing methane mitigation efforts through the CBG sector.

TERI conducted detailed site visits and interviews to gather comprehensive data on the operation and challenges of CBG plants. In-person visits included detailed walkthroughs with plant owners and operators, during which relevant operational data, such as real-time biogas production data, were recorded from equipment where possible. For non-operational plants, TERI conducted virtual interviews with owners and operators to collect valuable insights. The study team used a standardized questionnaire, (refer to Appendix B) to ensure consistency in data collection across all facilities. This questionnaire captured both qualitative and quantitative information for each plant.

Qualitative data focused on challenges and successes related to feedstock procurement, purification technology, staffing, and market linkages for CBG and digestate. Quantitative data captured key operational parameters including feedstock storage and processing, biogas production, and technical performance of the purification system.

The study team analyzed the detailed qualitative and quantitative data across all plants to identify opportunities and challenges that CBG plants in India and in other parts of the world may face. EPA developed summary reports for each plant categorizing the findings into five core areas: feedstocks, purification systems, staff and training, end-product sales, and permitting and financing. The analysis of this study yielded actionable recommendations aimed at equipping government agencies, project developers, and NGOs with necessary tools to support the efficient development and operation of CBG plants for reducing methane emissions. By directly addressing the identified challenges, the study offers recommendations to bolster methane mitigation efforts, ensuring the sectors alignment with national and global sustainability goals. These recommendations are designed to enhance the CBG sector's capacity to convert diverse organic waste streams into clean energy effectively, reducing methane emissions while contributing to energy security and environmental resilience.

3. Overview of the CBG Production Process

Biogas is produced through the anaerobic digestion of organic matter resulting in a mixture primarily composed of methane (55–65 percent) and carbon dioxide (30–40 percent) along with trace amounts of other gases such as hydrogen sulfide (0.1–4 percent), nitrogen (about 3 percent), oxygen (0.1–2 percent) and moisture (1–2 percent). In comparison, CBG is biogas that has undergone purification to remove impurities like carbon dioxide, hydrogen sulfide and moisture, followed by compression at high pressures. The purification and compression of biogas increases the methane concentration to more than 90 percent and enhances its calorific value from approximately 19.5 megajoules per kilogram (MJ/kg) for raw biogas to about 47–52 MJ/kg for CBG primarily making it a renewable alternative to conventional fossil fuels.

In India, CSTR is a commonly used type of anaerobic digester. It continuously processes organic waste in an oxygen-free (anaerobic) environment using a stirring mechanism that keeps the feedstock contents evenly mixed to produce biogas and digestate. The biogas thus produced has a methane percentage ranging from 55 to 65 percent depending on the type of feedstock, efficiency of the digestion process, and operating conditions. Figure 1 shows the step-by-step process in the production of CBG in India.

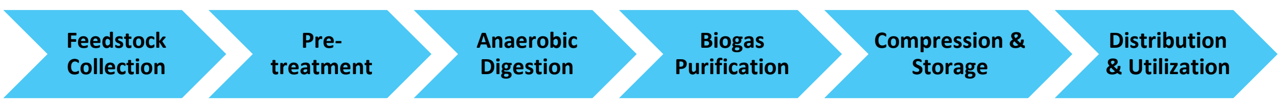


Figure 1. Step-by-Step process of CBG production

1. Feedstock Collection

The CBG production process in India begins with sourcing diverse organic waste streams including agricultural residues, food waste, MSW, and animal manure. Agricultural residues such as crop stubble, sugarcane press mud and corn stalks provide a significant share of feedstock, especially in the intensive farming regions of northern India. Animal manure from cattle and poultry is another dominant feedstock given its consistent supply and high methane yield. While food waste and MSW are abundant in urban areas, their use in biogas production is relatively infeasible due to challenges in segregation and variability in organic content.

The magnitude of available feedstock is substantial. For instance, India's agricultural sector generates about 500 million tons of crop residues[10] and over a billion tons of animal manure every year,[11] of

[10] Meena, H.N., Singh, S.K., Meena, M.S., Narayan R. & Sen,B. (2022). Crop Residue: Waste or Wealth? Technical Bulletin 1/2022, ICAR- Agricultural Technology Application Research Institute, Zone-II, Jodhpur. https://krishi.icar.gov.in/jspui/handle/123456789/71699

[11] Parihar,S,S., Saini,K.P.S., Lakhani,G.P., Jain,A., Roy,B., Ghosh,S & Bhavna, A.(2019) Livestock waste management: A review. Journal of Entomology and Zoology Studies; 7(3): 384-393 https://www.entomoljournal.com/archives/2019/vol7issue3/ PartG / 6-6-95-692.pdf

which a significant portion is suitable for biogas production. Feedstock collection in India is either centralized or decentralized depending on the waste source and composition. Centralized waste collection is common in urban areas where food waste and MSW are aggregated from multiple sources and transported to a single processing facility. Meanwhile, in rural areas, decentralized waste collection systems are prevalent, in which agricultural residues and animal manure from cow shelters and farms are transported to a nearby CBG plant. Facilities may use co-mingled waste streams, such as combining agricultural residues with animal manure to optimize anerobic digestion parameters, particularly the carbon–nitrogen ratio. Others rely on single-source feedstocks leveraging consistent waste streams from sugar mills or dairy farms. Feedstock collection practices vary by the CBG facility depending on the local feedstock availability, economic considerations, and technology requirements.

2. Pre-treatment

The collected feedstock undergoes a pretreatment process that involves sorting out non-biodegradable materials that could hinder the digestion process. Sorted organic materials can be mechanically processed through shredding or grinding to increase the surface area of the feedstock and thereby enhance the action of the methane-forming microorganisms (methanogens).

3. Anaerobic digestion

The feedstock is loaded into the anaerobic digestor. The controlled anaerobic environment (devoid of oxygen) in the digestor facilitates the growth of methane-producing microorganisms that break down organic matter to produce biogas. Raw (unpurified) biogas is made up of methane (55–65 percent), carbon dioxide (30–40 percent), and other trace gases. The effluent that is left after the feedstock is processed in the digestor is called “digestate,” which is often separated into solid and liquid components that have applications in agriculture as a nutrient-rich soil amendment.

4. Biogas Purification

The raw biogas undergoes a purification process to increase the methane content to 95–99 percent by removing impurities such as hydrogen sulfide, carbon dioxide, and excess moisture. The purification process enhances the calorific value of biogas, making it suitable for power generation, heating and transportation, and other applications. The common methods used for purification include water scrubbing, PSA, VPSA, and MST.

Water scrubbing uses water to absorb carbon dioxide and hydrogen sulfide from raw biogas, resulting in an enriched methane stream. It involves pressurizing the biogas and passing it through a scrubber, a column filled with water in which carbon dioxide and other impurities dissolve, leaving behind methane-rich biogas. Biogas purified using this method can reach up to 95 to 98 percent methane concentration.

PSA uses a series of adsorption beds filled with aluminosilicates like zeolites to separate methane from other gases. Raw biogas passes through the adsorbent beds at high pressure, and aluminosilicates selectively adsorb carbon dioxide and other impurities while methane passes through. Methane concentrations can reach up to 97 to 98 percent using this method while the energy requirements are higher than water scrubbing.

VPSA is similar to PSA, but it operates at lower pressure and uses vacuum pressure for methane separation. This technology is popular in India, due to its lower cost compared to other purification methods.

MST uses selective permeable membranes to separate methane from other components in biogas. Using VPSA and MST the methane concentration can reach up to 96 to 99 percent.

The choice of these systems in India often depends on factors such as investment capability of the company, energy costs, scale of operation, and desired purity levels of biogas.

5. Compression and Storage

Following purification, the gas is compressed using high pressure, typically around 200 to 250 bars (approximately 2,900 to 3,600 pounds per square inch), which reduces the gas volume significantly and increases feasibility for transporting the gas and injecting it into the natural gas grid or for using the gas in other ways. The compressed biogas, called CBG, is stored in specialized cylinders designed to maintain high pressure of the gas and ensure its safety.

6. Distribution and Utilization

The CBG cylinders are transported to filling stations or directly to the end-users depending on the infrastructure and demand in a particular region. Quality control measures throughout the process ensure the CBG cylinders meet the quality requirements for their intended use and safety of the users. CBG finds its application primarily as a green alternative to fossil fuel with applications in transportation, power generation, industrial heating, and domestic uses.

In India, CBG facilities are financed through a mix of government incentives, private investments and public-private partnerships. The national programs such as SATAT play a crucial role in providing financial support and market linkages to promote CBG production. Under SATAT, oil marketing companies offer purchase agreements to CBG producers guaranteeing offtake and creating a reliable revenue stream.[12] Additionally, various government schemes support the sector through capital cost subsidies, low-interest loans and grants for equipment and infrastructure for fostering methane capture and utilization. The economic viability of methane mitigation through CBG production remains contingent upon multiple interconnected factors, including feedstock availability, operational efficiency and market demand for CBG and its by-products. Significant financial risk persists stemming from fluctuating feedstock costs, high operational expenses, and limited local markets for by-products. Effective management coupled with enabling policies and market support is essential for leveraging the methane mitigation potential of CBG facilities.

[12] Sustainable Alternative Towards Affordable Transportation (SATAT). (2022). Home page. https://satat.co.in/satat/#/

4. Participating CBG Plant Characteristics

The analysis of 11 CBG plants across northern India highlights their operational features and role in methane emission mitigation. These plants use a variety of organic feedstocks including cow dung, poultry litter, press mud, sewage sludge and MSW to produce biogas through anaerobic digestion. By subsequent purification, they capture and convert methane, a potent GHG, into CBG for energy applications. Seven of these plants remain active, while four are inactive due to operational and financial challenges. TERI conducted site visits and interviews to gather quantitative and qualitative data on plant operation, CBG purification technology, biogas production, biogas end-use, operational staff requirements and training, feedstock types, and other factors that contribute to plant successes and challenges Table 1 contains operational profiles for each plant included in this report. Figure 2 represents the sites on a map. Figures 3, 4, and 5 visually represent the distribution of characteristics across the sites.

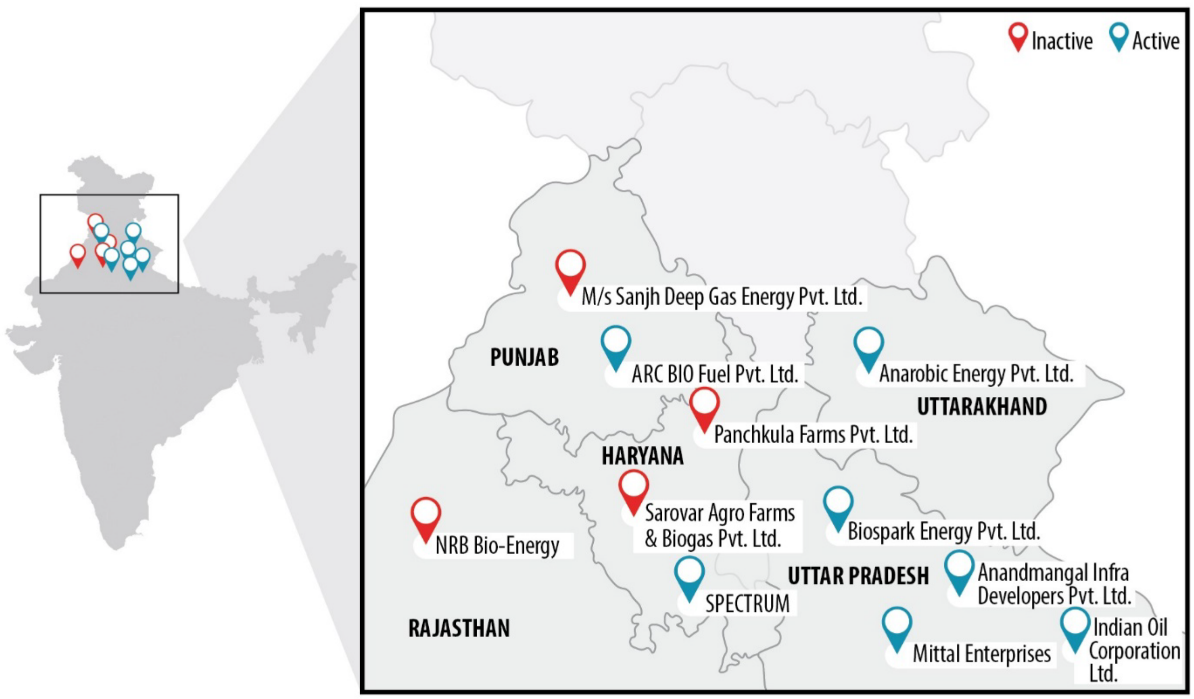


Figure 2 Map Representation of CBG Plant Sites

Table 1. Operational Profiles of CBG Plants Included in the Study

CBG Plants	Status	Location	Years in Operation	Feedstocks	Biogas End Use	Purification System	Operational Headcount
M/s Sanjh Deep Gas Energy Private Limited	Inactive	Bathinda, Punjab	2012-2016	Cow dung	Commercial cooking fuel	VPSA	4
NRB Bio-Energy	Inactive	Hanumangarh, Rajasthan	2013-2017	Cow dung	Commercial cooking fuel	VPSA	8
Panchkula Farms Private Limited	Inactive	Panchkula, Haryana	2016-2019	Poultry litter, cow dung, press mud, corn stalks	Commercial cooking fuel	VPSA	8
Sarovar Agro Farms & Biogas Private Limited	Inactive	Ambala, Haryana	2016-2021	Cow dung, poultry litter	Commercial cooking fuel	VPSA	10
Arc Bio Fuel Private Limited	Active	Barnala, Punjab	2013-present	Cow dung; poultry litter	Commercial cooking fuel	VPSA	15
Spectrum Renewable Energy Private Limited	Active	Rohtak, Haryana	2020-present	Press mud, cow dung	Vehicle fuel	MST	45
Biospark Energy Private Limited	Active	Muzaffarnagar, Uttar Pradesh	2023-present	Press mud, cow dung	Utility natural gas grid	VPSA	16
Mittal Enterprises	Active	Hapur, Uttar Pradesh	2023-present	Press mud, poultry litter, cow dung	Vehicle fuel	Water scrubbing	25
Anarobic Energy Private Limited	Active	Jagjeetpur, Haridwar, Uttarakhand	2023-present	Press mud, sewage sludge	Vehicle fuel	MST	20
Anandmangal Infra Developers Private Limited	Active	Meerut, Uttar Pradesh	2023-present	Press mud, cow dung	Vehicle fuel	VPSA	12
Indian Oil Corporation Limited (IOCL)	Active	Gorakhpur, Uttar Pradesh	2024-present	Press mud cow dung paddy straw	Vehicle fuel	VPSA	40

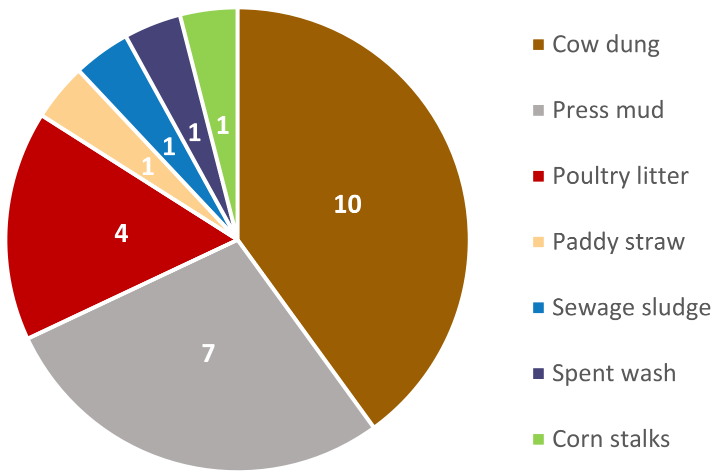


Figure 3 Number of Plants per Feedstock Type

The plants use CSTR systems for anerobic digestion generating raw biogas that contains methane concentrations ranging from 55 to 65 percent depending on feedstock composition. To enhance the utility of methane in the biogas, the raw biogas undergoes purification to increase the methane content to as high as 97 to 98 percent. Biogas with this methane content has multiple use cases.

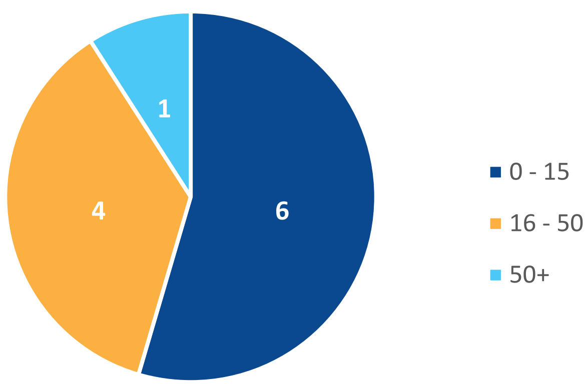


Figure 4 Number of Plants per Operational Staff Level

Different purification technologies used across the participating plants are tailored to their specific operational needs. VPSA systems are most widely used due to their availability and cost-effectiveness. Advanced methods such as MST and water scrubbing are also used in some facilities offering better methane recovery.

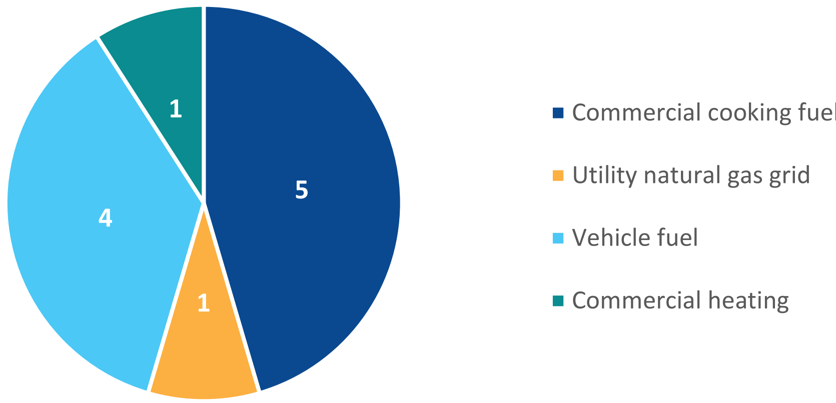


Figure 5 Number of Plants per CBG End-Use

The operational capacities of these plants vary according to their design specifications and feedstock availability. Active plants such as Arc Bio Fuel Private Limited and Biospark Energy Private limited demonstrate efficient methane recovery, supported by advanced purification systems. For instance. Arc Bio Fuel Private Limited uses cow dung and poultry litter as feedstock to produce high purity CBG which is used as commercial cooking fuel. Similarly, Biospark Energy injects its CBG into the natural gas grid enabling the use of purified methane for household and industrial applications.

Methane emission mitigation is central to the functionality of these plants. By capturing methane (or biogas) during the anaerobic digestion process CBG facilities prevent its release into the atmosphere which would contribute significantly to global warming. Instead, the captured methane is used as a renewable energy source. For instance, the IOCL plant is expected to operate at a designed biogas production capacity of 25,217 m^3/day producing 20,000 kg of CBG/day. Even during its testing phase, it achieves substantial methane capture, operating at 70 percent capacity. Infrastructure supporting these operations such as storage, purification systems further enhance methane recovery and use. Facilities like Mittal enterprises and Anandmangal Infra Developers Private Limited efficiently combine diverse feedstocks to maintain consistent biogas output. Their integrated purification and storage systems ensure the captured methane is available for downstream applications including transportation fuel and commercial heating. The operational features of the participating CBG plants underline their role in methane emission mitigation and the potential to address climate change while contributing to a sustainable energy economy.

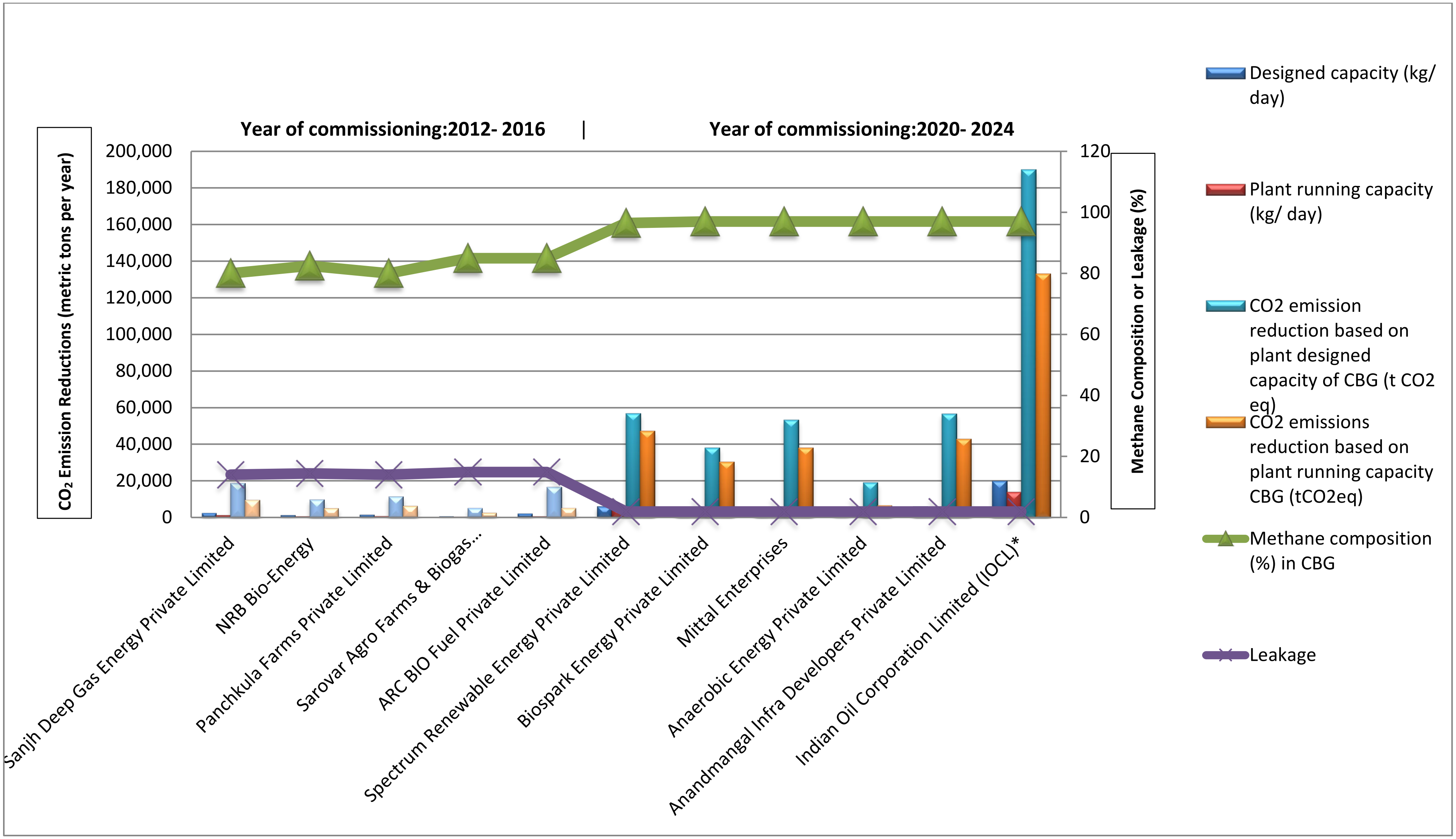
Table 2 provides a detailed overview of the 11 plant's performance metrics such as the designed and actual methane mitigation potential of the CBG plants and its impact on the total GHG reduction. Key indicators such as designed and actual capacities for biogas (methane) and CBG production, methane composition in the output, and total GHG reduction potential highlight the operational efficiency and environmental contributions of these facilities.

Table 2. Performance Metrics and Environmental Impacts of CBG Plants

CBG Plant	Designed capacity for biogas production (m^3/day)	Designed capacity for CBG production (kg/day)	Methane composition in CBG (%)	Total carbon dioxide emission reduction potential (Designed capacity metric ton CO_2e)	Plant running capacity (CBG kg/day)	Total carbon dioxide emission reduction (based on plant running capacity metric ton CO_2e)	Number of days plant operational*	Total GHG reduction (based on plant running capacity metric ton CO_2e)	Total GHG reduction (based on Design capacity metric ton CO_2e)
1. M/s Sanjh Deep Gas Energy Private Limited	6,000	2,400	80	18,816	1,200	9,408	1,750	45,107	90,214
2. NRB Bio-Energy	2,500	1,200	80-85	9,702	600	4,851	3,150	41,865	83,730
3. Panchkula Farms Private Limited	3,500	1,450	80	11,368	800	6,272	1,400	24,057	43,603
4. Sarovar Agro Farms & Biogas Private Limited	1,500	600	85	4,998	300	2,499	2,100	14,377	28,756
5. Arc Bio Fuel Private Limited	5,000	2,000	85	16,660	600	4,998	4,164	57,018	190,061
6. Spectrum Renewable Energy Private Limited	15,000	6,000	96-97	56,742	5,000	47,285	1,369	177,351	212,821
7. Biospark Energy Private Limited	10,000	4,000	96-98	38,024	3,200	30,419	406	33,836	42,295
8. Mittal Enterprises	14,000	5,600	96-98	53,234	4,000	38,024	652	67,922	95,091
9. Anarobic Energy Private Limited	5,000	2,000	96-98	19,012	700	6,654	571	10,410	29,742
10. Anandmangal Infra Developers Private Limited	13,600	5,960	96-98	56,656	4,500	42,777	366	42,894	56,811
11. Indian Oil Corporation Limited (IOCL)	25,217	20,000	96-98	190,120	14,000	133,084	579	211,111	301,588

*Number of days plant operational represent the total operational duration of the plant from the start of CBG production until study data were gathered. For the IOCL plant, data collection was during the testing phase operations with calculations based on an assumed 70% running capacity of the designed output.

Figure 6: Performance Metrics and Environmental Impact of CBG Plants



The data analysis clearly shows that active plants contribute significantly to methane emission reductions by converting organic waste such as cow dung, poultry litter and press mud into biogas and further into CBG. For instance, IOCL has demonstrated high efficiency with the designed CBG capacity of 20,000 kg/day achieving methane composition levels of 96–98 percent. This high methane capture efficiency underscores the plant's contribution to substantial GHG reductions. Similarly, Spectrum Energy and Biospark Energy Private Limited maintain methane compositions exceeding 96 percent further emphasizing the potential of advanced purification systems in maximizing methane recovery.

On the other hand, inactive plants like M/s Sanjh Deep Gas Energy Private Limited and NRB Bio-Energy reported 80–85 percent methane compositions and lower operational efficiencies due to challenges such as feedstock disruptions, inefficient purification systems limiting higher methane capture. These plants operated significantly below their designed capacities, leading to reduced actual GHG reductions compared to its potential.

The data in Table 2 reveal a direct correlation between feedstock type and methane recovery efficiency. Feedstocks with higher methane yield such as press mud and cow dung enable plants like IOCL to achieve higher operational capacities and GHG reductions. Conversely, inactive plants had challenges with inconsistent or seasonal feedstocks, which significantly impeded methane mitigation. The detailed analysis highlights the role of CBG plants in reducing methane emissions and emphasizes the importance of addressing challenges to unlock their full potential.

5. Identified Challenges and Opportunities

This section discusses the study team's findings from the site visits and interviews in the following topic areas: feedstocks, purification systems and other equipment, staff and training, end-product sales, and permitting and financing. The sequence of the topic areas mirrors the lifecycle of a CBG project from inception to implementation and operation. For conciseness, individual plants mentioned in this section are referred to using a shortened version of their company name as listed in Table 1. For example, Panchkula Farms Private Limited is referred to as "Panchkula."

5.1 Feedstocks

The availability, cost, and quality of feedstock play a vital role in methane capture contributing to the success of CBG plants. This section explores the dynamics that biogas plants face in securing a reliable and cost-effective feedstock supply.

i. Pricing and Agreements

CBG plants in India face major challenges related to volatility in feedstock pricing and its consistent supply. Several plants experienced operational disruptions due to price uncertainty and feedstock supply shortages. One plant (NRB) ceased its operations following a 40 percent hike in feedstock price resulting from a lack of formalized legal agreements. For another inactive plant (Sarovar), which relied on cow dung as a feedstock, the price of dung doubled due to the COVID-19 pandemic, which led to logistical disruptions, increased demand for organic manure in agriculture due to fertilizer supply challenges, and labor shortages. The increase in feedstock price led to increased operational costs, which made the plant unprofitable to operate and resulted in its shutdown. A third inactive plant (Sanjh) struggled with the inflated cost of raw materials due to the demand for feedstock generated by the SATAT program.

Despite price and supply fluctuations, six plants demonstrated successful feedstock procurement arrangements by establishing contractual agreements with suppliers. These contracts ensured consistent pricing and feedstock availability, contributing to operational stability. One active plant (Mittal) with a diverse feedstock mix including press mud, poultry litter, cow dung, and spent wash collaborated with sugar mills, farmers in local villages, and dairies to secure a steady supply of feedstock through formalized agreements. Three other active plants (IOCL, Spectrum, and Biospark) have signed short-term contracts with sugar industries and *gaushalas* (cow shelters) and have not experienced issues with supply or collection of feedstocks.

Another active plant (Anarobic) secured contractual agreements with the nearby sugar industry for the procurement of press mud. Notably, this plant also secured an eight-year agreement with a government body for sewage sludge procurement, demonstrating the importance of long-term contracts for financial stability.

ii. Sourcing and Storage

Reliable feedstock sourcing and storage presented additional challenges for eight of the plants. One inactive plant (Panchkula) initially relied on readily available poultry litter, but because poultry units were not removing the litter regularly, its availability to the biogas operators became an issue for consistent operations. This was coupled with community concerns regarding the odor from the feedstock stored for use in the biogas plant. In addition, the seasonal nature of certain feedstocks, such as press mud (which is available only six months a year during the sugarcane harvesting and sugar processing season), led to an inconsistent supply of feedstock for some plants. Inadequate storage facilities in plants using press mud as a feedstock further complicated these concerns, with four plants (Mittal, Spectrum, Biospark, IOCL) reporting significant feedstock loss due to exposure to environmental factors like rain and sun. In addition, these plants did not have the basic laboratory facilities for measuring the carbon-to-nitrogen (C: N) ratio, which is important for the microorganisms to actively break down the feedstock for biogas production. These plants reported having to operate digesters below design capacity due to insufficient feedstock supply, which resulted in lower biogas generation and less profit.

5.2 Purification Systems and Other Equipment

Biogas purification, crucial for converting raw biogas into usable CBG, presents a complex landscape for plant operators. This section explores the successes and challenges that various plants face in their choice and operation of purification equipment.

i. Technology Selection and Operation

Selecting the appropriate purification technology is important for converting raw biogas into CBG. The efficiency and maintenance requirements of these technologies vary, making it essential to balance cost-effectiveness with operational ease. For example, one inactive plant (Sanjh) chose a VPSA system since it was convenient for the company to source the technology. However, the installed system lacked features such as sulfur and carbon dioxide recovery, leading to only 80 percent efficiency in biogas production. The shortcomings of the purification system resulted in high operational costs and decreased CBG production. Sulfur and carbon dioxide recovery improves the quality of CBG and prevents the corrosion of equipment; these recovered products can also generate new revenue streams.

Other plants (Anandmangal, IOCL, Biospark) achieved efficiencies of 90 to 99 percent using VPSA technology without significant maintenance concerns. The operators attributed the success of these plants to the adherence to strict and proactive maintenance schedules including continuous servicing of equipment such as motors and compressors.

Conversely, the plant (Spectrum) that opted for the equipment classified as “best-in-class” faced operational issues due to missing manuals and high service costs for their MST system. This resulted in high equipment service costs and extended wait times, impacting operational efficiency.

ii. Standards and Sustainability

Adherence to the national purification standards, particularly Indian Standard (IS) 16087, which mandates a methane content of at least 90 percent and less than 4 percent carbon dioxide levels, is crucial for ensuring high quality CBG. IS16087 is the Indian Standard for biogas that outlines the requirements and methods of sampling and testing for biogas applications in stationary engines, automotive and thermal applications, and supply through piped networks. One plant (Spectrum) uses

MST system that achieves high methane content (over 96 percent) and minimal leakage in order to comply with the IS 16087 standard, allowing the plant to directly inject biogas into vehicular fuel.

None of the plants in this assessment have taken the additional step of recovering elemental sulfur and carbon dioxide. Recovering elemental sulfur and carbon dioxide improves biogas quality by increasing methane concentration and reducing harmful emissions, resulting in fuel efficiency and environmental safety. In addition, elemental sulfur and carbon dioxide have economic value, creating additional revenue streams and improving economic viability of biogas projects.

iii. Lack of Monitoring Data

A significant challenge identified was the absence of monitoring systems across the many CBG plants. Eight CBG plants (Sanjh, NRB, Panchkula, Sarovar, Biospark, ARC, Mittal, and Anandmangal) had not received monitoring equipment from the purification technology providers, which prevented the assessment of biogas production, methane leakage, and purification effectiveness. This lack of data hinders operational optimization, and one plant (NRB) reported 20 to 30 percent biogas loss due to the absence of a monitoring system where gas exited the anaerobic digester.

iv. Equipment and Knowledge Gaps

Two inactive plants (NRB, Sanjh) encountered problems with the quality of equipment and lack of technical support from the technology providers, leading to operational inefficiencies and fluctuating biogas production. Another active plant (Biospark) faced similar issues, with their technology provider supplying lower-efficiency equipment. The operators' lack of technical knowledge further exacerbated these issues, highlighting the need for thorough research and transparency when selecting technology providers.

v. Commissioning

The commissioning phase posed significant challenges due to the absence of standardized policies and guidance for biogas plants. Two inactive plants (Sarovar and Sanjh) had to develop their own standards for the anaerobic digester, biogas production, and feedstocks and persevered through initial technical difficulties, achieving operational stability and design capacity over time. The Sarovar plant achieved just 50 percent of its working capacity within three years. Another active plant (Spectrum) displayed resilience by overcoming technical challenges and fluctuating efficiency, which initially resulted from the lack of standardized guidance. Through persistent monitoring and iterative trials over a period of six to seven months, Spectrum was able to overcome low biogas outputs and stabilize its operations to reach design capacity. These observations demonstrate the importance of innovation and resilience during commissioning, as well as the need for standardized commissioning guidelines.

5.3 Staff and Training

Staffing and training play a vital role in the smooth operation of a biogas plant. This section summarizes the experiences of the CBG plants in managing their workforce.

i. Investing in Expertise

Several active plants have created comprehensive staff training programs. One plant (Anandmangal) received support from its technology provider, which trained 12 employees, and achieved 75 percent efficiency within three months of commissioning. Another plant (Biospark) fostered a knowledge-sharing culture, with trained staff guiding and training others, enhancing overall operational efficiency of the CBG plant.

ii. Filling the Labor Gap

Recruiting skilled labor can be challenging, especially for tasks like handling cow dung. One inactive plant (Sarovar) addressed this concern by training the existing staff, demonstrating the importance of adaptability and upskilling.

5.4 End-Product Sales

This section examines the critical role of end-product sales in the financial viability of biogas plants in India. It identifies key challenges in offtake, storage, and digestate sales while highlighting successful strategies that some plants have employed.

i. Offtake and Storage

The study team observed a mismatch in the production of biogas by the CBG plants and the purchase capacity of the oil and natural gas companies. One plant (Anandmangal) reported that the buyer (a private company through the SATAT program) of CBG was not in a position to purchase the entire quantity of biogas produced by this plant, which resulted in revenue losses ranging from 10 to 20 percent. This highlights the need for better coordination and communication between biogas plants and CBG purchasing companies participating in programs like SATAT to align production with purchase agreements.

In addition, storage of CBG was a major challenge. One plant (Biospark) supplying biogas to Indraprastha Gas Limited faced operational inefficiencies since that company had no pipelines close to biogas production and the CBG plant had no storage facilities. Biospark had to inject the CBG into the pipeline of another company, Gas Authority of India Limited, and encountered challenges due to limited injection time windows. This plant had a 16-hour window to inject the gas into the pipeline, but gas production occurs during the entire day. Any additional investment in storage systems would increase the plant's expenditure; without additional storage, this plant has to run at two-thirds of its capacity, generating less biogas and resulting in losses. There is a need for CBG plants to invest in storage infrastructure and explore flexible injection schedules to maximize plant efficiency and biogas utilization.

ii. Digestate Sales

Two inactive plants (NRB, Sarovar) reported insufficient budget for processing digestate into marketable products. Another plant (Anarobic) struggled to find buyers for both the liquid and solid digestate. This highlights the importance of conducting market research for developing products that could be made from digestate as part of the initial business plan. In addition, the CBG plants should identify grants or other financial incentives for acquiring digestate processing equipment to develop value-added products. The plants' experiences also highlight the need to market linkages between CBG plants and potential digestate buyers such as agricultural sectors or fertilizer manufacturers.

iii. The Value of Diversification

One active plant (Anarobic) successfully diversified its revenue streams by selling CBG through its own filling stations and using digestate as manure for agricultural purposes. Another plant (Biospark) injected CBG directly into the natural gas pipeline network, catering to household needs. Biospark also uses the digestate as manure on nearby farms, demonstrating waste reduction and resource recovery. These successes warrant the integration of CBG plants with existing natural gas infrastructure and expansion market research.

5.5 Permitting and Financing

Biogas plant projects, despite their environmental and economic benefits, can face significant hurdles in securing permits and financing. This section explores the challenges CBG plants encountered in navigating these critical stages. The observations aim to provide insights into effective strategies and recommend policy interventions to streamline these processes for supporting the CBG sector.

Permitting

One active plant (Anarobic) encountered significant delays in government approvals during the project development phase. The experience of another active plant (Biospark) further emphasizes this challenge, citing a lack of awareness among local authorities regarding the required permits. This underscores the need for better communication and streamlined procedures for biogas plant permitting.

Financing

Three plants (Biospark, Mittal, and Sarovar) also encountered difficulties securing project financing due to financial institutions' lack of knowledge about CBG plants and the perceived risks associated with these projects. One active plant (Mittal) reported difficulties because rural banks were not aware of policies on loans for biogas plants. However, another active plant (IOCL) that received funding from its parent company, encountered no permitting, financing, or construction obstacles. This highlights the need for transparency, collaboration, financial literacy, and improved communication between biogas developers and financial institutions.

6. Summary of Lessons Learned and Recommendations

This section summarizes the observations, lessons learned and recommendations of the study team's findings from the site visits and interviews in the following topic areas: feedstocks, purification systems and other equipment, staff and training, end-product sales, and permitting and financing.

6.1 Feedstocks

The study team's observations regarding the successful and unsuccessful plants on feedstock challenges are discussed below.

Successful plants demonstrated the following activities:

1. Strong relationships with community stakeholders

Six biogas plants developed trusted relationships with local dairy farmers and villages for procuring cow dung, which led to signing formal agreements. The Anarobic plant operators collaborated with municipal bodies for sourcing sewage sludge as a feedstock for anaerobic digestors. Collaborations or partnerships can evolve through good relationships with community stakeholders and allow plants to secure a reliable supply of organic waste materials.

2. Consistent feedstock supply and pricing

The Mittal plant established formal agreements or contracts with feedstock suppliers, ensuring a steady and predictable flow of feedstock and pricing for uninterrupted biogas production.

Unsuccessful plants demonstrated:

1. No relationship with community stakeholders

The NRB plant ceased its operations following a 40 percent feedstock price hike resulting from a lack of formal legal agreements. For another inactive plant (Sarovar), which relied on cow dung as a feedstock, the price of dung doubled during the COVID-19 pandemic. This price hike was attributed to logistical disruptions and increased demand for organic manures in agriculture due to fertilizer supply challenges and labor shortages.

2. No deep understanding of technical parameters like C:N ratio

No biogas plants had basic laboratory facilities to analyze the C:N ratio of feedstock prior to adding it to the CBG plant. Establishing basic laboratory facilities is crucial to ensure quality and consistency in production.

3. Feedstock storage issues

Due to the exposure to environmental factors like sun and rain, the Mittal plant, which uses press mud as a feedstock, lost about 10 to 50 percent in quantity and 10 to 70 percent quality degradation. These losses affected the overall production of biogas and increased input costs.

4. Lack of long-term contracts

The inactive plants (Panchkula, NRB, Sanjh, Sarovar) did not establish long-term contracts with feedstock suppliers which created price and supply fluctuations and resulted in its closure.

Recommendations:

The following recommendations represent potential actions that may improve the efficiency and effectiveness of feedstock agreements within the CBG industry.

- **Standardization of agreements.** Develop a set of comprehensive guidance documents and template agreements for feedstock procurement. These resources should be readily available to CBG industry stakeholders and address challenges in feedstock agreements.
- **Supplier partnerships.** Facilitate establishment of long-term contracts and negotiation between the industry and reliable suppliers of feedstock to foster stability of supply chains, promote predictability of pricing structures, and incentivize responsible sourcing practices throughout the industry.
- **Quality control.** Implement standardized protocols for feedstock quality assessment such as C:N ratio estimation to provide consistency and reliability in the evaluation of feedstock quality and suitability for CBG production.
- **Adequate storage facilities.** Invest in adequate storage facilities for feedstock to preserve product quality and optimize operational efficiency. Proper storage will not only minimize spoilage and deterioration due to the exposure of feedstock to environmental factors but also maintain its consistent supply for uninterrupted production processes.
- **Knowledge transfer.** Develop and deliver industry-wide training programs to create awareness of ideal feedstock profiles tailored to the requirements of CBG production. Such programs should develop toolkits guiding stakeholders on optimal operating conditions to maximize the utilization efficiency of procured feedstock.

6.2 Purification Systems and Other Equipment

The observations of the study team regarding the purification systems and other equipment are discussed below.

Successful plants demonstrated the following activities:

1. The use of efficient purification systems

The Anandmangal, IOCL, and Biospark plant used efficient CBG purification systems that removed impurities, including sulfur and carbon dioxide, achieving up to 99 percent efficiency in gas production.

2. The use of maintenance standards

The Anandmangal, IOCL, and Biospark plants also adhered to strict maintenance standards, which contributed to smooth operations and minimized downtime due to equipment failures.

3. Compliance with gas purity standards

The Spectrum plant complies with the quality standards of CBG (IS 16087), which was used as alternative fuel for transportation, while Biospark has injected the gas into the city gas distribution network. Since the Government of India launched the SATAT initiative in 2018, all CBG plants comply with IS 16087 standards.

Unsuccessful plants demonstrated:

1. Inefficient purification systems

The Sanjh plant used a relatively inefficient PSA system with poor-quality molecular sieves and low-quality purification accessories, and it was only able to achieve 80 percent efficiency in biogas production.

2. Lack of equipment to recover sulfur or carbon dioxide

None of the plants in this assessment used equipment to recover sulfur and carbon dioxide, which represents a missed opportunity for additional revenue streams.

3. Eight of the plants noted that they lacked monitoring systems, with one plant in particular (NRB) stating that this lack of a monitoring system resulted in up to 30 percent loss of biogas production.

4. Insufficient technical knowledge among operators

The NRB and Sanjh plants noted that a lack of technical support from technology providers was exacerbated by insufficient technical knowledge among the plant operators, leading to significant inefficiencies in plant operations.

Recommendations:

The following recommendations represent potential actions to improve the operational efficiency of purification systems and maintenance requirements.

- **Research and due diligence.** Conduct thorough research and due diligence while procuring equipment and require clear maintenance protocols and technical support from technology providers.
- **Monitoring systems.** Implement comprehensive monitoring systems to track biogas production, methane leakage, and purification effectiveness.
- **Capacity building.** Provide thorough operator training and technical knowledge development to improve operational efficiency and identify technical problems.
- **Standardized policies.** Establish standardized policies for commissioning and guidance to address any technical concerns.
- **Transparency and knowledge sharing.** Encourage transparency and knowledge sharing among technology providers and plant operators.

6.3 Staff and Training

The study team's observations of successful and unsuccessful plants regarding staff and training challenges are discussed below.

Successful plants demonstrated two key strategies.

1.Capacity building

The Anandmangal plant received support from the technology provider for training 12 employees and achieved 75 percent operational efficiency within three months. It demonstrated the impact of well-designed training programs on plant performance. Investing in comprehensive training programs equips staff with the necessary knowledge and skills to operate the plant efficiently by minimizing errors and optimizing resource utilization, which results in higher biogas production.

2. Knowledge-sharing culture

The Biospark plant fostered a knowledge-sharing culture, where their trained staff actively guided and trained others, creating an environment of continuous learning and skill development that resulted in enhancing the overall competence of the workforce.

Unsuccessful plants demonstrated:

1. Labor recruitment challenges

The Sarovar plant faced significant difficulties in recruiting skilled labor for specific tasks, such as handling cow dung and consistently loading it into the CBG plants, resulting in operational inefficiencies.

2. Adaptability and upskilling

Three inactive plants (Sanjh, NRB, Panchkula) lacked the ability to address labor gaps and upskilling requirements for their labor force.

Recommendations:

The following recommendations represent potential actions to enhance the competence of the CBG operator's workforce.

- **Capacity-building programs.** Implement training programs focused on the specific needs of CBG plants operators.
- **Knowledge exchange between technology providers and operators.** Ensure that technology providers share knowledge on standard operating procedures with plant operators.
- **Knowledge-sharing culture.** Promote a culture where experienced staff members mentor and train newer employees to ensure continuity and shared expertise.
- **Labor gaps.** Develop strategies early on to recruit and train staff for tasks like handling cow dung to avoid operational delays.

6.4 End-Product Sales

The observations of the study team regarding end-product sales by the successful and unsuccessful plants are discussed below.

Successful plants demonstrated the following activities:

1. Diversification of revenue streams

The Anarobic plant demonstrated the effectiveness of a diversified approach to end-product sales. By selling CBG through their own filling stations and using digestate as a soil amendment they diversified revenue streams. This strategy not only maximizes the value of all plant outputs but also reduces dependency on a single product, enhancing overall financial stability.

2. Integration with existing infrastructure

One plant (Biospark) showcased the benefits of integrating biogas production with established energy distribution networks. By injecting purified biogas directly onto the natural gas pipeline network, they could access the broader market. Additionally, their approach of using digestate in nearby farms demonstrates effective resource recovery and waste reduction, aligning with circular economy approaches.

Unsuccessful plants demonstrated:

1. Misalignment with the CBG buyers

The Biospark plant was unable to sell full production capacity of their CBG to the oil and gas company due to the time window for injecting CBG into their pipeline, which was only 16 hours per day. Since biogas is produced throughout the day, this plant had to operate below capacity and bear the loss of biogas that could have been produced during the remaining 8 hours in a day. This underscores the importance of developing appropriate policy frameworks for the oil and gas companies to purchase all the biogas produced by the CBG plants through national initiatives like SATAT.

2. Inadequate planning for by-product value addition

The NRB plant failed to add value to the digestate for generating additional revenue streams. Their lack of budget for by-product value addition and market research for digestate utilization demonstrates the importance of developing appropriate value-added products by understanding the potential markets before commencing operations.

Recommendations:

The following recommendations represent potential actions to increase project revenue and ensure financial sustainability.

- **Conduct market research.** Conducting market research before and during plant operations is crucial to prioritize demand patterns for CBG and potential markets for products developed from digestate. Government initiatives like SATAT could support this effort by providing market intelligence and facilitating linkages between CBG producers and potential end-users.

- **Invest in storage solutions.** Investment in storage facilities is essential for ensuring continuous and efficient CBG plant operations. Government support through various financial instruments such as grants, subsidies, or low-interest loans for storage infrastructure could significantly enhance plant productivity and profitability.
- **Implement marketing strategies.** CBG plants should explore diverse marketing strategies for the sale of CBG and invest in the development of value-added products from digestate for agricultural purposes.
- **Leverage national initiatives to create a regulatory framework.** National initiatives like SATAT could provide financial and regulatory support for creating an enabling environment for CBG stakeholders. Governments should consider reviewing existing policies to address the challenges faced by the CBG sector.

6.5 Permitting and Financing

The observations of the study team on how the successful and unsuccessful plants handled permitting and financing are discussed below.

Successful plants demonstrated the following activities:

1. Leveraging support from national initiatives

IOCL, being a government subsidiary organization, avoided the financial challenges faced by the other private CBG companies. It highlights the government support to the CBG sector which is nascent.

2. Navigating bureaucratic challenges

Anarobic faced significant delays during the project phase due to bureaucratic hurdles in permitting, so the active plant created its own standards to navigate the permitting process. This activity highlights the need to create awareness among all the government agencies and financial institutions of permitting regulations and financial instruments to promote the CBG sector.

Unsuccessful plants demonstrated:

1. Challenges in securing financing

Sarovar had challenges in securing funding because the financial institutions lacked knowledge about CBG projects.

Recommendations:

The following recommendations represent potential actions to overcome permitting and financing barriers for CBG projects.

- **Improve permitting procedures.** Establish a streamlined system for permitting requirements for CBG projects with clear timelines and requirements to reduce delays and uncertainties that discourage investments and hinder project commissioning. Capacity development initiatives to enhance local authorities' awareness of and expertise in CBG project evaluation could facilitate addressing permitting challenges.

- **Raise awareness of financial institutions.** Facilitate knowledge sharing and consider developing comprehensive toolkits for financial institutions on CBG project economics, risks, and business opportunities to minimize the knowledge gap and reduce perceived risks.
- **Develop insurance mechanisms.** Develop insurance mechanisms to mitigate perceived risks and also to encourage private sector lending to biogas projects.
- **Enable public-private partnerships (PPPs).** To leverage the strengths of both the government and private sector, developing a framework for PPPs in the CBG sector could enable private companies to benefit from government support while bringing in private sector expertise and capital.
- **Incentivize collaboration.** Incentivizing collaboration with established CBG companies by offering tax incentives or a low-interest credit line may facilitate knowledge sharing and risk mitigation.

7. Summary and Conclusions

This report presents a critical analysis of the CBG sector in India, emphasizing its role in mitigating methane emissions and thus contributing to substantive GHG abatement efforts. The study team assessed 11 CBG plants in northern India representing diverse operational capacities, feedstock types and purification technologies to evaluate the potential of CBG plants as a scalable and sustainable solution for methane mitigation. The findings highlight the significant contribution of these plants to reduce methane emissions and identify the economic and operational barriers that limit the scalability and effectiveness.

Methane, with a GWP 28 times that of CO_2, is one of the most potent GHGs contributing to climate change. The CBG sector offers a strategic pathway for mitigating methane emissions by capturing methane from organic waste streams such as cow dung, poultry litter, press mud and sewage sludge, which would otherwise be released to the atmosphere. The operational data along with the performance metrics of the 11 CBG plants demonstrate the efficiency of anaerobic digestion and purification technologies in transforming methane into diverse energy applications. For example, plants like Arc Bio Fuel Limited and IOCL could achieve up to 99 percent methane recovery rates demonstrating the technical feasibility of large-scale methane capture.

To fully realize the methane mitigation potential of CBG plants the findings of this study highlight the urgency of addressing critical barriers that constrain its growth. Volatile feedstock prices (such as a 40 percent price increase in cow dung during the COVID-19 pandemic), limited long-term supply agreements, and logistical challenges in securing consistent feedstock supplies undermine the reliability of CBG production. Additionally, high operational costs with gaps in technical capacity and infrastructure deter investment and development. Eight of the 11 plants did not have real-time monitoring systems resulting in 20-30 percent methane losses during purification. These challenges were evident in inactive plants such as M/s Sanjh Deep Gas Energy where operational disruptions led to significant gap in methane capture capabilities.

The methane emission reduction potential in India's CBG sector is substantial. According to Government of India data, India generates about 3 million tons of cow dung every day which can generate about 180 million m^3/day of biogas with a methane mitigation potential of 144 million m^3/day of methane, which would mitigate 2.7 MMT of CO_2e/day. Similarly other feedstocks such as press mud, poultry litter and agricultural residues have tremendous potential for producing CBG and generating new revenue streams while simultaneously mitigating methane emissions. Additionally, using the digestate in agricultural systems can not only improve soil health and reduce dependence on synthetic fertilizers but also contribute to sustainable land-use practices.

India's NDC's aim to reduce GHG emissions intensity by 45 percent from 2005 levels by 2030 and achieve 50 percent renewable energy capacity in power generation. The SATAT initiative aims to establish 5,000 CBG plants targeting 15 million tons of biogas annually. To promote the use of indigenous feedstock in sustainable aviation fuel, a mandatory 1 percent CBG blending with natural gas will start in 2025, which will progressively increase in subsequent years.

Though the CBG sector in India demonstrates a pathway for methane mitigation, realizing its full potential requires overcoming economic and operational barriers. Enabling policies must focus on stabilizing feedstock markets, incentivizing infrastructure investments, and building technical capacity across the sector. Fostering public-private partnerships and streamlining the permitting process could catalyze greater investment and operational efficiency. By leveraging the insights from this report, stakeholders can advance the development of the CBG sector ensuring that it not only contributes to India's climate commitments but also serves as a global model for methane mitigation.

Appendix A. Summary of Purification Technologies

This section summarizes the advantages and disadvantages of the biogas purification technologies used by the plants included in this study. The table below shows the actual efficiency and methane loss achieved by the plants, as well as feedback on cost, performance, and operation and maintenance reported by plant owners and operators. Note that the efficiencies listed below are based on the projects' real-life experience based on actual operations of the purification technologies, and they do not necessarily reflect manufacturers' claimed performance ratings.

All technologies demonstrated the potential ability to achieve the high methane content required to meet the necessary CBG quality standards, (IS 16087) established by the Bureau of Indian Standards (BIS). VPSA system performance was the most variable among plants, and not all plants achieved the methane content needed for CBG (at least 90 percent). Some VPSA systems also experienced inconsistent gas production due to operational and maintenance issues. Still, VPSA systems were the most prevalent purification technology among the plants, due to the wide availability, ease of use, and lower initial cost compared to other technologies.

MST does not appear to be a widely used technology in India, and one plant experienced equipment delays that disrupted plant operations. Water scrubbing proved to be a high-efficiency purification technology that is simpler to operate and requires less maintenance than VPSA. Water scrubbing requires significant water consumption, which adds additional operational cost compared to other technologies.

Biogas Purification Technology Advantages and Disadvantages

Purification technology	Operational Performance	Advantages	Disadvantages
Pressure Swing Adsorption	• 80-99% efficiency • 0.5-20% methane loss	• Capable of high efficiency • Easy to use • Lower initial cost	• Variable performance • Inconsistent gas production • High maintenance costs • Higher energy consumption
Vacuum Pressure Swing Adsorption	• 96-98% efficiency • <2% methane loss	• High efficiency • Lower energy consumption	• High maintenance costs
Membrane separation technology	• 96% efficiency • 3% methane loss	• High efficiency • Lower energy consumption	• High maintenance costs • Not widely available; extended equipment delays impacted operation
Water Scrubbing	• 98% efficiency • <1% methane loss	• High efficiency • Least technically complex • Low maintenance costs	• Requires significant water consumption

Appendix B: Questionnaire for CBG Plant Site Visit or Virtual Interview

1. Site physical details

Name of biogas plant	
Location of Biogas plant	
Contact person	
Operating company	
Mode of operation (private/Government/PPP)	
Company address	
Phone, e-mail, and website	
Plant developer's details (technology provider)	
Procurement and Commissioning details	
Date of commissioning (month/year)	
Date of plant closure (month/year) if applicable	
Site details	
Land area for construction	
Soil texture	
Groundwater level	
Ambient temperature	

2.Type of plant

3. Challenges and Lessons Learned

What challenges did you encounter during the project phase (e.g., permitting, financing, construction, system start-up)? How did you overcome these challenges?	
What challenges have occurred since the plant was commissioned? How did you overcome these challenges?	

What advice would you give to future digester owners/operators?	

4.Details of Feedstock

Do you have agreements in place for acquiring feedstocks? How did you find and acquire feedstocks?			
Have you had any issues with feedstocks? (e.g. inconsistent quality/quantity)			
Have you had any challenges with storing feedstocks?			
How do you determine the right mixture of feedstock?			
Do you have a feedstock management plan? (If yes, ask detailed questions below. If no, skip.)			
	Feedstock 1	**Feedstock 2**	**Feedstock 3**
Name of feed stock			
Mixing ratio			
Amount [mt/d]			
Biogas yield (m^3/ton)			
Biogas yield from mixture of feed stocks	……………………………………………………..m^3/ton		

5.Details of operational conditions and parameters

Capacity of the plant	Biogas: CBG:
Feedstock collection mechanism, transportation, and procurement rate (from cooperatives/door-to-door, etc.)	
Feedstock storage capacity	
Type of storage (feedstock)	

Mechanism of feedstock transfer to next step	
Pre-processing of feedstock	
Type of pre-processing	
Space for pre-processing	
During pre-processing, any environmental and health hazard observed or expected	
Type of digestion (wet/dry and % TS feed)	
Raw material to water ratio	
Digester	
Digestate storage capacity	
Separation of digestate (yes/no)	
Use of digestate (yes/no)	
Operating temperature [°C]	
Retention time [d] for digestion	
Recirculation (yes/no) mass [m^3/d]	

6.Details of the Gas Purification System

Purification technology type(s)	
Why did you choose this type(s) of technology? Is it meeting expectations?	
Have you had any issues with the purification system? If yes, explain.	
Has the purification system needed any maintenance or repairs? If yes, please provide information on costs, wait times, and any disruption to normal operations.	
Which purification standards are you using for CBG?	
Initial Cost of the Purification System	
Annual operating costs of the purification system	
Actual efficiency of technology	
Are you implementing advanced purification to remove high levels of H_2S, VOCs, siloxanes, N_2, or O_2? If so, explain.	
Recovery of elemental Sulphur	
Recovery of CO_2	
Loss of methane/leakage from purification process	
What happens to the tail gas from the purification process?	

7.Operational Health/safety

How many employees are required to operate the biogas plant?	
How are employees trained?	
What health and safety standards are followed?	
Have you had challenges recruiting or retaining employees? If yes, what steps are you taking to recruit and retain employees?	

8. Additional information/Annexure

- ❖ Services (operation/maintenance/inspection/monitoring):
- ❖ Documentation:
- ❖ Have you carried out an environmental impact assessment for your plant? Certified copy of EIA:
- ❖ Certifications/standards followed:
- ❖ Social nuisance during feedstock collection and storage (Odors/Flies, etc.) (assessed by interview observation):
- ❖ Plant schematic:

Appendix C: Calculation Methodology

1. Biogas Production from cow dung

The following assumptions are made for calculating the biogas production from 3 million tons of cow dung per day.

On average, 1 kilogram (kg) of cow dung produces 0.04 to 0.06 m^3 of biogas per day.

Calculation:

Estimated Biogas production (Lower range) = 3 million tons/day x 0.04 m^3/kg

= $3x10^9$ kg/day x 0.04 m^3/kg

= $1.2x10^8$ m^3/day

= **120 million m^3/day**

Estimated Biogas production (Higher range) = 3 million tons/day x 0.06 m^3/kg

= $3x10^9$ kg/day x 0.06 m^3/kg

= $1.8x10^8$ m^3/day

= **180 million m^3/day**

2. Methane Mitigation through Anaerobic digestion

The following are the assumptions.

Global warming Potential (GWP) of methane =28

Volatile solids (VS) content in cow dung after digestion = about 20% of the cow dung weight

Methane density = 0.67 kg/m^3

Methane emission factor = 0.24 m^3 of methane/kg of volatile solids

Calculation:

VS produced/day = cow dung produced/day x volatile solids content

= $3x10^9$ kg/day x 0.20

= **$6x10^8$ kg/day**

Methane emissions = VS/day x emission factor

= $6x10^8$ kg/day x 0.24 m^3/kg

= 1.44 x 10^8 m^3/day

= **144 million m^3/day**

CO_2e mitigation = Methane weight x GWP

Convert methane volume to weight = methane volume x methane density

Methane weight = 1.44×10^8 m^3/day x 0.67 kg/m^3

= **9.65×10^7 kg/day**

Now, CO_2e mitigation = 9.65×10^7 kg/day x 28

= 2.70×10^9 kg/day CO_2e

= **2.70 million metric tons of CO_2e/day**