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Why Indian CBG Plants Underperform: A Loss Decomposition Framework Linking Feedstock Supply, Process Stability, Downtime and Upgrading Losses

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Abstract

India's Compressed Biogas (CBG) programme now has about 210 functional plants, supported by an assured buyer under the SATAT initiative and a blending obligation that has been mandatory since FY 2025 to 26. Regulator data show that these plants delivered only 44 percent of their rated capacity in the first half of FY 2026 to 27, and that plants without a pipeline connection performed markedly worse. This review proposes a loss decomposition framework that traces CBG output from nameplate capacity to saleable gas through five sequential losses: feedstock availability, design basis overestimation, biological conversion, downtime, and upgrading and offtake. For each stage we synthesise Indian policy, regulatory and supply studies, full scale evidence from Germany, Denmark and China, and plant experience, and define indicators that allow the loss to be measured on site. Because each loss acts on the output left by the one before, moderate shortfalls compound and can halve delivered gas without any single dramatic failure. The evidence suggests that seasonal feedstock supply, design yields taken directly from laboratory methane potential tests and offtake logistics account for much of the gap, and that all three are largely fixed before construction. Process instability and downtime depend more on operating practice and support, while methane slip remains unmeasured in India. We propose design basis corrections, utilisation based due diligence for lenders, generation linked policy support and a minimum monitoring dataset that would allow the gap to be measured and managed.

Keywords: Compressed biogas; Capacity utilisation; Anaerobic digestion; SATAT; Feedstock supply chain; Process stability; Plant performance benchmarking; India

Abbreviations

AD	Anaerobic digestion	**MSW**	Municipal solid waste
BMP	Biochemical methane potential	**PNG**	Piped natural gas
CBG	Compressed biogas	**SATAT**	Sustainable Alternative Towards Affordable Transportation
CBO	CBG blending obligation	**TPD**	Tonnes per day
CGD	City gas distribution	**TS / VS**	Total solids / volatile solids
CNG	Compressed natural gas	**VFA**	Volatile fatty acids
EPC	Engineering, procurement and construction		

1. Introduction

1.1 Growth of compressed biogas in India and the policy context

India has tried to build a biogas economy several times. The household digester programmes of the 1980s and 1990s spread millions of small units across rural districts, and the Waste to Energy schemes that followed added municipal and industrial plants. The current attempt differs in one respect that matters. Since the launch of the Sustainable Alternative Towards Affordable Transportation (SATAT) initiative in October 2018, biogas is no longer treated mainly as a cooking fuel or a by product of sanitation, but upgraded to Compressed Biogas (CBG), a product with a defined specification, a guaranteed buyer in the public sector oil marketing companies, and a price linked to compressed natural gas [1, 2].

Policy support has widened since then. The city gas distribution network has been opened to CBG injection, and in November 2023 the National Biofuels Coordination Committee announced a CBG blending obligation for the transport and domestic piped gas segments. Blending was voluntary until FY 2024 to 25 and became mandatory at 1 percent in FY 2025 to 26, rising to 3, 4 and 5 percent over the following three years. The obligation was expected to draw investment of about Rs 37,500 crore into roughly 750 projects by FY 2028 to 29 [3]. By September 2026, 210 CBG plants were functional, with a combined rated capacity of 2,212 tonnes per day, an average of roughly 10 tonnes per day per plant [4]. Growth has come mainly from small and medium plants built largely by first generation entrepreneurs [5].

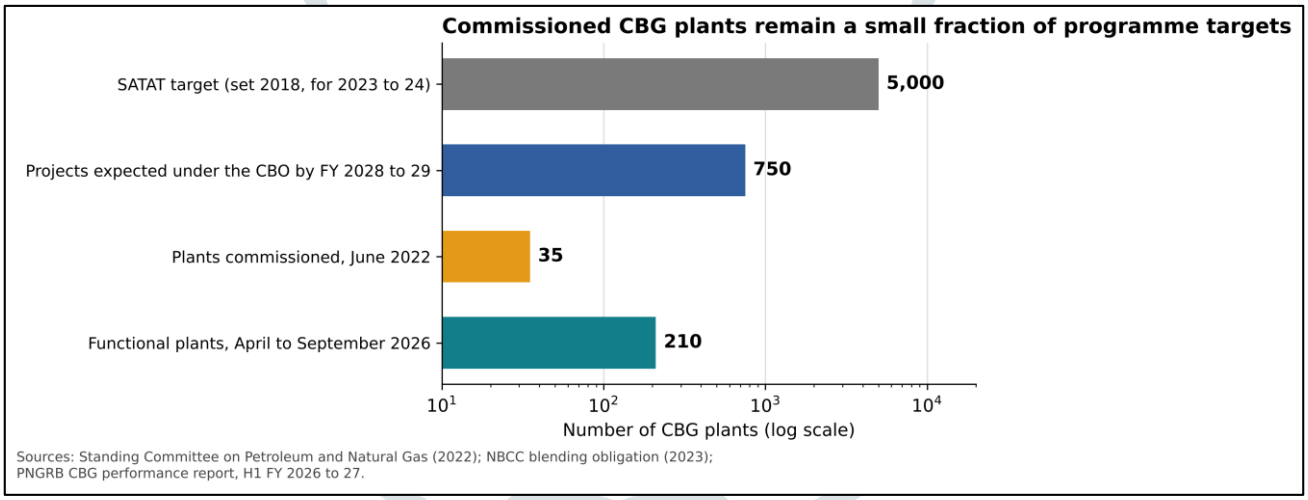

Fig. 1. Commissioned CBG plants compared with programme targets. The SATAT target and the 2022 commissioning figure are from the Standing Committee on Petroleum and Natural Gas [6]; the expected project count under the blending obligation is from [3]; the count of functional plants is from the regulator [4]. Note the logarithmic scale.

1.2 The capacity utilisation gap: evidence and consequences

Programme statistics count plants and sum their nameplate capacity. They say little about how much gas those plants actually sell. When the Standing Committee on Petroleum and Natural Gas reviewed SATAT in December 2022, it found that 35 plants had been commissioned against a target of 5,000, while 3,263 letters of intent had been issued, many of them to the same entrepreneurs [6]. The Committee listed the reasons: weak returns on a price pegged to CNG, multiple approvals, the withdrawal of central financial assistance, and feedstock that is available for only a few months of the year and therefore demands large storage yards [6]. Those are reasons why plants are not built. They are also, plausibly, reasons why plants that are built do not run at their rated output.

Until recently, public data on that second question did not exist. The Petroleum and Natural Gas Regulatory Board (PNGRB) has now begun to publish them, and the figures are sobering. Between April and September 2026, the 210 functional plants produced 982 tonnes per day against a rated capacity of 2,212 tonnes per day, a utilisation of 44 percent [4]. CBG reached 0.92 percent of CNG and domestic piped gas sales in FY 2025 to 26 against an obligation of 1 percent [7], and 1.7 percent in the first half of FY 2026 to 27 against an obligation of 3 percent [4]. The same report shows that about 73 percent of CBG was moved by cascade trucks, that 133

functional plants holding three quarters of rated capacity had no plan for a pipeline connection, and that connected plants ran at about 65 percent of rated capacity compared with about 40 percent for the rest (Fig. 2) [4]. History points the same way. India's record with waste to energy plants includes a long list of units that were commissioned, ran poorly and were eventually idled [8]. China's rural biogas programme, which grew on capital subsidies, left a large share of its installed digesters underused or abandoned [9]. Recent assessments of SATAT era plants point to the same feedstock, technical and operating problems at commercial scale [1, 5], and in the authors' experience many of these problems were foreseeable at the feasibility stage.

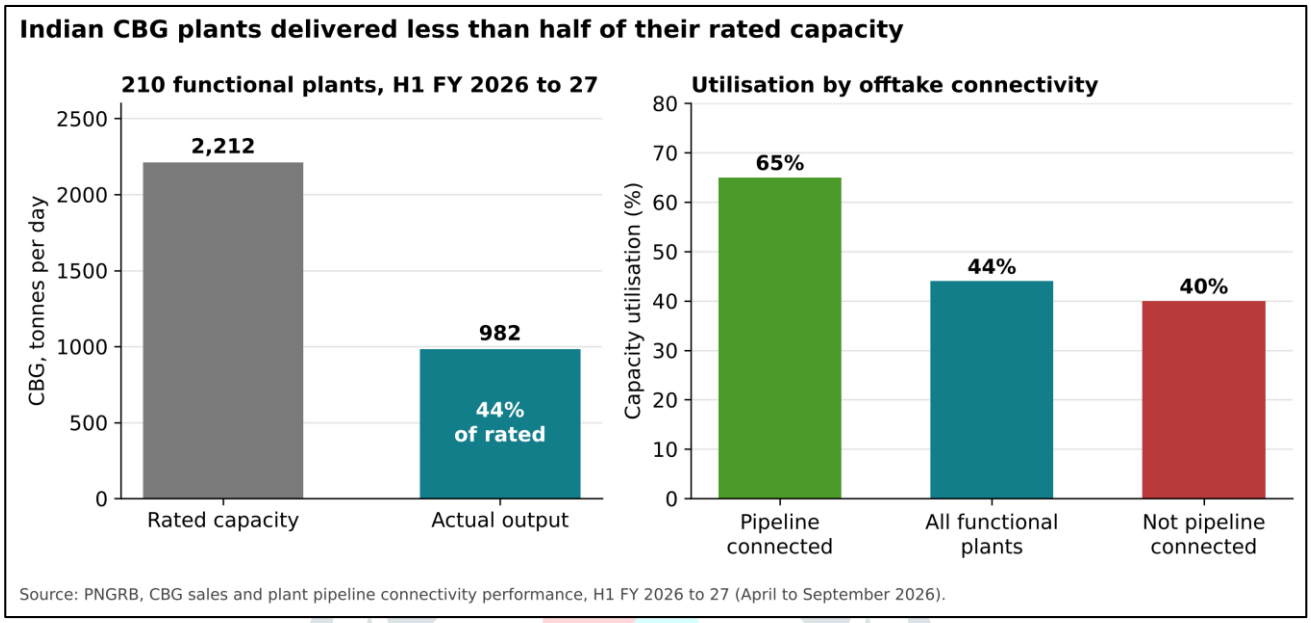

Fig. 2. Capacity utilisation of Indian CBG plants in the first half of FY 2026 to 27. Left: rated capacity and actual output of the 210 functional plants. Right: utilisation of pipeline connected plants, all plants and plants without a pipeline connection, as reported by the regulator [4].

The consequences go beyond individual balance sheets. A plant whose debt is sized on nameplate output and which operates at less than half of it will struggle to service that debt, and every such case raises the risk premium that lenders apply to the next project. For the blending obligation, a fleet that underdelivers means gas distributors cannot meet their quota from domestic CBG. For carbon markets, credit estimates based on design rather than metered output undermine the integrity of the whole category. Whether the programme succeeds will depend on capacity utilisation far more than on the number of plants.

1.3 Limitations of existing reviews

Several reviews have examined biogas and CBG in India, and they are valuable. Mittal and colleagues classified barriers to biogas dissemination into financial, technical, institutional and market groups [10]. Breitenmoser and colleagues surveyed opportunities and research needs for anaerobic digestion of Indian biowastes [11]. More recent work has assessed the status of SATAT era plants [1], ranked the hurdles that CBG developers face [5], and evaluated the techno economic performance of CBG from agricultural residues [12]. Table 1 summarises their scope.

What these reviews share is a qualitative treatment of underperformance. They tell us which problems exist, but not how much of the missing output each problem removes, nor how the problems interact. A developer reading them cannot decide whether to spend the next rupee on feedstock storage, a better feeding system or a stability monitoring programme. A lender cannot tell which assumption in a detailed project report is most likely to fail. This review attempts to move from listing barriers to quantifying the losses they cause.

Table 1. Scope of recent reviews of Indian biogas and CBG, and the contribution of the present review.

Review	Year	Main focus	Treatment of underperformance
Mittal et al. [10]	2018	Barriers to biogas dissemination	Qualitative barrier taxonomy; no plant level losses
Breitenmoser et al. [11]	2019	Opportunities and research needs for Indian AD	Operational problems listed; not quantified
Singh et al. [1]	2023	Status and technology of CBG plants	Challenges described; no loss accounting
Ghag et al. [5]	2025	Hurdles facing CBG plants	Hurdles ranked by perception, not by output lost
Kulkarni et al. [12]	2025	Techno economics of residue based CBG	Utilisation treated as an input assumption
This review	2026	Capacity utilisation gap	Five stage loss decomposition with measurable indicators

1.4 Aim, scope and contribution of this review

This review asks three questions. Where, between nameplate capacity and the gas meter at the point of sale, is output from Indian CBG plants lost? Which of those losses are best supported by evidence, and which are assumed rather than measured? And what would developers, lenders and policymakers need to measure to manage the gap?

To answer them, we propose a loss decomposition framework that divides the utilisation gap into five sequential losses: feedstock availability, design basis overestimation, biological conversion, downtime, and upgrading and offtake. Each loss is tied to the published evidence, to measurable indicators and to the practical experience of the authors, who have designed, commissioned and operated CBG plants on press mud, paddy straw, Napier grass, cattle dung and municipal organic waste. The scope is commercial CBG plants of roughly 2 to 20 tonnes per day, which make up most of the SATAT fleet. Household digesters and large captive power plants are discussed only where their experience carries over.

2. Review methodology

2.1 Search strategy and databases

This is a critical narrative review. Sources were identified through searches of Scopus and Web of Science, supplemented by Google Scholar, for literature published between 2008 and 2026, with emphasis on work after 2015. Search strings combined three groups of terms: the technology (biogas, biomethane, compressed biogas, Bio CNG, anaerobic digestion), the performance question (capacity utilisation, plant performance, full scale, process stability, downtime, methane loss) and the setting (India, SATAT, and named feedstocks such as paddy straw, press mud, Napier grass and municipal solid waste). Reference lists of included papers were then searched backwards to capture older studies that later work relies on.

2.2 Inclusion and exclusion criteria

Studies were included if they reported on full scale or pilot scale plant performance, on Indian feedstock supply, policy or plant experience, or on methods for measuring plant level efficiency and losses. Laboratory studies were included only where they bear directly on how design yields are set, for example biochemical methane potential testing. Studies confined to novel additives, nanomaterials or reactor concepts that have not reached commercial scale were excluded, since they say little about why existing plants underperform.

2.3 Screening and selection

Records were screened on title and abstract and then on full text, and duplicate preprints and conference versions of the same work were merged. Selection was purposive rather than exhaustive: the aim was to retain the studies that carry the argument, not to catalogue the entire anaerobic digestion literature. The resulting core set of 43 sources comprises peer reviewed articles, a small number of official and trade sources on programme status, and practitioner publications by the authors.

2.4 Quality appraisal and treatment of grey literature

Peer reviewed studies were given the greatest weight. Grey literature was admitted where it is the only source for a fact the argument needs, chiefly parliamentary committee findings and ministry announcements on SATAT and the blending obligation [3, 6], together with the regulator's reports on CBG sales and utilisation [4, 7]. Several practitioner publications by the present authors are also cited, because they record plant level observations that are not otherwise available in print; these are marked in the text as practitioner observations and are used to illustrate mechanisms rather than to establish magnitudes. Indian sources dominate the policy context and feedstock supply, while evidence on biological, downtime and upgrading losses comes mostly from European and Chinese full scale studies. That imbalance is itself one of the findings of this review.

3. Defining capacity utilisation for CBG plants

3.1 Nameplate, design and sustained capacity

Plant performance is often misjudged because the word capacity means different things at different stages of a project. A detailed project report states a nameplate figure, typically in tonnes of CBG per day. That figure assumes a feed rate, a specific methane yield (usually taken from biochemical methane potential, or BMP, tests), a number of operating days in the year and an upgrading recovery. Each assumption can be met or missed independently, so a plant can be correctly built and still never produce its nameplate output. Table 2 sets out the terms used in this review. Each intermediate term corresponds to the output remaining after one stage of loss, so that every loss is counted once. All terms are expressed in kilograms of CBG per day at the buyer's methane specification, so that stages measured in volatile solids or normal cubic metres of methane can be converted to a common basis.

Table 2. Capacity terms used in this review. Each term is the output remaining after the loss stage shown, so that no loss is counted twice.

Term	Definition	After stage	Typical source
Nameplate capacity	Rated CBG output at design feed rate, design yield and design operating hours	None	Detailed project report
Available capacity	Output at design yield from the volatile solids actually fed	L1	Feed records, storage records
Realisable capacity	Output from the volatile solids fed at the yield achievable under stable reference loading	L2	Continuous trials, stable operating periods
Stable process capacity	Realisable capacity less output lost to process upsets during operating hours	L3	Gas flow meters, process logs
Sustained capacity	Stable process capacity less output lost while equipment is stopped	L4	Operating hour records
Saleable output	CBG accepted and invoiced, net of methane slip, own use, flaring and rejected gas	L5	Offtake invoices
Capacity utilisation	Saleable output divided by nameplate capacity over the same period	All	Derived

3.2 Performance indicators from full scale benchmarking

Europe has a longer record of measuring full scale biogas plants, and four lessons from it carry over. First, plant performance can be expressed as a small set of indicators covering feedstock use, biological conversion, technical availability and energy use, which allows plants of different size and feedstock to be compared on a common basis [13]. Second, year round monitoring of agricultural plants in Germany and China showed that actual output could depart widely from design values, and that the gap was considerably larger at the Chinese plants, where operating support and process control were weaker [14]. Third, the biological efficiency of a full scale plant, meaning the share of the substrate's methane potential that is actually recovered, can be estimated by several methods that give different answers, so the method must be stated before any comparison is made [15]. Fourth, even a mature fleet does not run at nameplate: German biogas plants in regular operation averaged 7,086 full load hours in 2015, about 81 percent of the hours in a year, with overall plant performance estimated at 70 to 80 percent [16]. That range is a realistic benchmark against which Indian utilisation can be judged.

These studies show that a plant's shortfall is the product of several partial efficiencies, each with its own causes and remedies. Indian project documents rarely treat it that way, and the parts cannot be managed until they are measured separately.

3.3 The proposed loss decomposition framework

Building on that benchmarking logic [13, 15] and on our earlier practitioner work on the gap between laboratory and full scale performance [17], we propose the framework shown in Fig. 3. Output flows from nameplate capacity to saleable CBG through five stages, and each stage removes a share of what enters it. Each loss is defined as a share of the output entering its stage: L1 as one minus the ratio of volatile solids fed to design volatile solids; L2 as one minus the ratio of realisable yield to design yield; L3 as one minus the ratio of yield achieved during operating hours to realisable yield; L4 as one minus the ratio of operating hours to design hours; and L5 as one minus the ratio of CBG sold to the CBG equivalent of methane produced, which captures slip, own use in heating and compression, flaring and rejected gas. Because each loss acts on what remains after the one before, capacity utilisation equals the product of the five stage efficiencies.

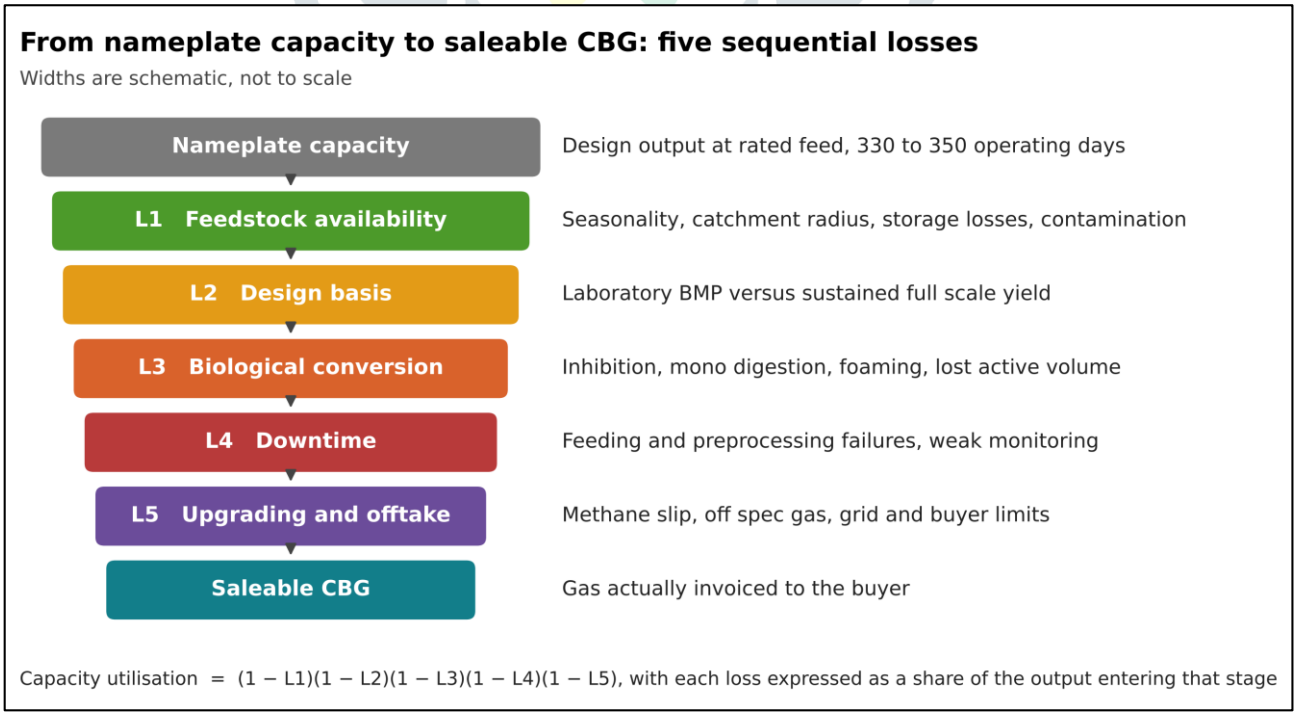

Fig. 3. The loss decomposition framework. Output passes from nameplate capacity to saleable CBG through five sequential losses, each with distinct causes and indicators. Box widths are schematic.

Fig. 4 applies the framework to three cases. The first is measured. A 3 tonne per day plant from the authors' portfolio averaged 2.56 tonnes per day over 18 months of operation, a utilisation of about 85.5 percent. In the 14 normal months it took about 73 tonnes of press mud a day and delivered 2.967 tonnes per day, or 98.9 percent of nameplate, a realised yield of about 40.6 kg of CBG per tonne of press mud. In the four lean months, press mud was available on only about half the days, at about 22.9 tonnes a day, and on the remaining days the plant ran on about 13 tonnes of bagasse a day instead; output averaged 1.157 tonnes per day. Assuming that press mud kept its normal yield, the shortfall cost about 18.5 points of utilisation over the 18 months, the bagasse substitution recovered about 5.1 points, and all other losses together came to about 1.1 points. The implied bagasse yield, about 106 kg of CBG per tonne, is derived by difference, so it also absorbs any carry over of gas from earlier press mud feeding and any change in press mud yield at lower loading. The plant sits above the 70 to 80 percent range of the German fleet [16] and far above the national average of 44 percent [4], and nearly all of its remaining loss comes from a single feedstock problem.

The decomposition also points to the remedy. Bagasse replaced only about 28 percent of the output lost to the press mud shortage. On the derived yields, fully covering the lean months would have needed an average of about 24 tonnes of bagasse a day across those months rather than 6.5. Whether the digester could accept that much, given the slower degradation of lignocellulosic bagasse and the need to keep nutrients in balance, is a question for trials rather than arithmetic. Either way, investment should go first into press mud storage or a larger, well managed second feed, not in process equipment.

No operating data have been published for an Indian paddy straw or Napier grass CBG plant, so the second case comes from China. A corn straw biogas plant at Fuyu, in the cold north east, takes about 30,000 tonnes of straw a year and feeds a 2 MWe combined heat and power unit. Its reported generation of about 16 million kWh a year corresponds to roughly 91 percent of rated output, and it had run for more than 30,000 hours by 2021 [18]. The plant reached that level by tackling the losses this review identifies: straw is crushed below 3 cm and ensiled under compressed film, which the operators report cuts dry matter loss by about 80 percent compared with open storage; total solids in the digester are held at 8 to 10 percent with combined mixing and recirculation to stop floating crusts; and engine waste heat keeps the digesters warm through the northern winter [18]. The figures are operator reported, refer to electricity rather than CBG, and are not broken down by stage, but they show that a straw plant can run close to nameplate when storage, mixing and temperature are engineered rather than assumed.

The third case is illustrative and shows how losses compound when several stages are weak at once. In a hypothetical 10 tonne per day plant, the feedstock shortfall is 15 percent, the design yield is 14 percent above what the plant can realise, and process upsets, downtime, and upgrading and offtake each remove a further 12 percent of the output reaching them. No single figure would alarm an operator, yet together they leave the plant selling about half of its rated output, not far from the national average [4], although that average is not broken down by cause. The values are assumptions chosen to show the arithmetic, not measurements. The three cases differ in one essential respect: well run plants lose output at one stage, or have engineered the losses out, while an average plant loses it at several.

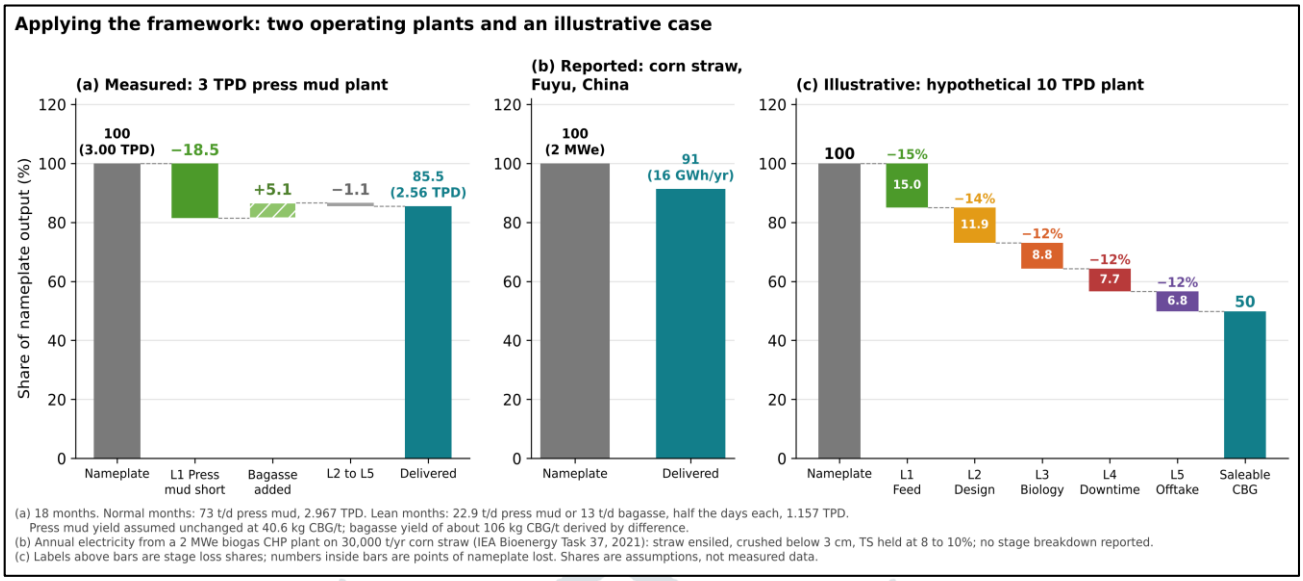

Fig. 4. The framework applied to (a) a measured 3 tonne per day press mud plant over 18 months of operation, where a seasonal press mud shortage removed about 18.5 points of output and substitution with bagasse recovered about 5.1, (b) a corn straw biogas plant in China that runs at about 91 percent of rated output after addressing storage, mixing and winter heating, as reported by the operator [18], and (c) a hypothetical 10 tonne per day plant in which moderate losses at every stage compound to halve output. Values in (c) are assumptions chosen to demonstrate the accounting, not measured data.

Table 3 links each stage to its main mechanisms, to the indicators that would allow it to be measured on site, and to the evidence reviewed in Sections 4 to 8.

Table 3. Loss stages of the framework, their main mechanisms and the indicators that allow each to be measured.

Stage	Main mechanisms	Measurable indicators	Section
L1 Feedstock availability	Seasonality, catchment limits, storage losses, contamination	Tonnes received and fed against design, by month; volatile solids loss in storage	4
L2 Design basis	Laboratory BMP used as design yield; benchmark feedstock assumptions; poor characterisation	Yield in a stable reference period against design yield	5
L3 Biological conversion	Inhibition, mono digestion instability, foaming, lost active volume	Yield during operating hours against realisable yield; VFA to alkalinity ratio	6
L4 Downtime	Feeding and preprocessing failures, weak monitoring, slow technical support	Operating hours, unplanned stops, mean time to repair	7
L5 Upgrading and offtake	Methane slip, own use, off specification gas, grid and buyer limits	Upgrading recovery, own use, flared volume, gas offered against accepted	8

4. Loss 1: Feedstock availability and quality

In our experience, and in the account given to Parliament [6], feedstock is the first place where output goes missing. A digester cannot produce gas from material it never receives, and the loss at this stage is set before the plant is even built: by the size of the catchment, the structure of supply contracts and the space allowed for storage.

4.1 Resource potential versus collectable supply

National estimates of biogas resource potential are large. Bottom up modelling of crop residues, livestock manure and municipal waste suggests that India's theoretical biogas resource could support output many times the present CBG fleet [19]. State level assessments, however, show that only a small part of that potential is used, and that the gap between potential and use varies widely between states [20]. The difference reflects not a shortage of biomass but the distance between what exists in a district and what a single plant can collect, store and pay for at a price that keeps the project viable.

Feasibility reports often blur that distinction. A district level surplus figure is quoted, a collection efficiency is assumed, and the plant is sized against the result. What the report rarely shows is a signed supply contract for each month of the year. Where supply depends on informal arrangements with farmers or aggregators, the plant carries the full risk of every season that turns out worse than average.

4.2 Seasonality of paddy straw and press mud

Two feedstocks prominent among SATAT projects in north and west India are both seasonal. Paddy straw in Punjab and Haryana becomes available over a few weeks in October and November, in the narrow window between the rice harvest and wheat sowing that also drives open field burning [21]. A straw based plant must therefore buy, bale and store most of a year's feedstock within about two months, then draw it down for the remaining ten. Storage at that scale requires land, protection from rain and fire, and working capital, and the Standing Committee identified exactly this requirement as a constraint on the programme [6].

Press mud is tied to the cane crushing season, which in most Indian sugar belts runs for roughly four to six months [22]. Outside that window, a plant that relies on press mud alone either runs on stored material or stands idle. Stored press mud does not stay the same: it loses volatile solids and changes in composition while it waits, and its methane potential also varies from one mill and region to another [23]. Even a well run press mud plant is exposed. In the measured case in Fig. 4(a), the plant ran at almost full capacity for most of the year, yet the lean months, on reduced press mud with bagasse substituted, accounted for nearly all of its lost output. Fig. 5 summarises the typical availability of fresh feedstock through the year.

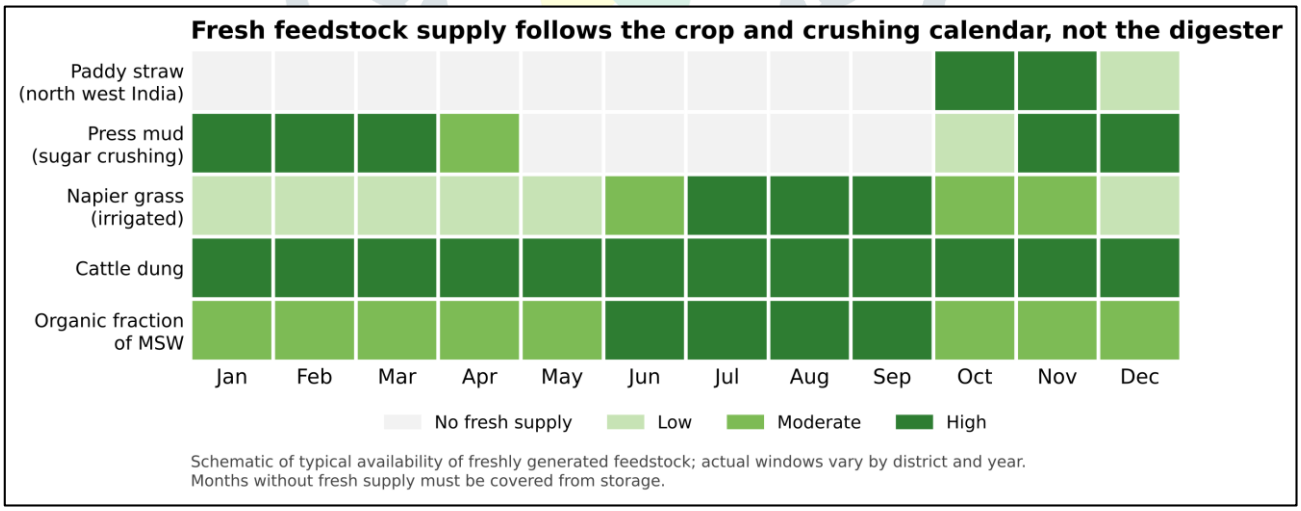

Fig. 5. Typical availability of freshly generated feedstock through the year for the main CBG substrates in India (schematic, based on [21, 22] and the authors' plant experience). Months without fresh supply must be covered from storage, with associated losses.

Seasonality turns into lost output in two ways. The obvious one is a plant that simply runs short in the lean months. The less obvious one is storage loss, the share of organic matter that degrades in bales, heaps or silage before it reaches the digester. Outdoor storage of large corn stover bales in Iowa lost between 5 and 17 percent of dry matter, depending on cover and duration [24]. Wet cereal straw baled and ensiled for biogas lost about 5 percent of its dry weight in well wrapped bales and about 10 percent in unwrapped bales, and poor wrapping reduced the methane potential of the stored straw by 17 to 30 percent [25]. At a full scale corn straw plant in China, ensiling under compressed film was reported to cut dry matter loss by about 80 percent compared with

open storage [18]. Storage losses are rarely measured at Indian plants, where bales often sit in the open through the monsoon, and a design that assumes none overstates available capacity from the first day.

4.3 Collection logistics and catchment limits

Straw is bulky, and its cost rises quickly with distance. A survey of straw supply in northern China found that farmers were willing to haul straw only about 3.2 km on their own initiative, and that larger volumes could be secured only when plants or intermediaries organised collection actively [26]. The setting differs, but the lesson transfers directly. A plant that relies on farmers to bring residue to the gate will collect from a small radius. A plant that wants a larger catchment must pay for balers, tractors, transport and aggregation, and those costs must appear in the financial model rather than being absorbed silently into an optimistic feedstock price.

4.4 Segregation and contamination of municipal organic waste

Plants fed with the organic fraction of municipal solid waste (MSW) face a different supply problem. Quantity is less seasonal, but quality depends on segregation at source, which remains weak in most Indian cities [27]. Plastics, glass, grit and other inerts arrive with the organic fraction, and each tonne of reject is a tonne of nameplate feed that produces no gas. Rejects also wear pumps, block screens and settle in digesters, so poor segregation shows up again later as downtime and lost active volume.

4.5 Energy crops: Napier grass yield and ensiling assumptions

Napier grass and other energy grasses are often proposed precisely because they avoid the seasonality of residues. They can be cut several times a year from the same field and ensiled for continuous feeding. In the authors' experience, project reports frequently assume field yields, cutting frequencies and methane yields drawn from the best trial plots, applied across the whole area under contract and every year of the loan. Rainfall, irrigation, fertiliser use, farmer attention and the quality of ensiling all pull real yields below those values. Ensiling itself has a cost: storage losses depend on moisture, fermentable sugar content, buffering capacity and packing density [28], and maize silage exposed to air at feed out lost up to 17 percent of its methane potential within seven days [29]. Silage face management therefore belongs in the feedstock budget. A feedstock plan that depends on energy crops should be built on conservative yields, and those yields should be checked against actual harvests before the plant commits to its full capacity, for example through a phased build.

Across all feedstocks, the first loss is mostly a contracting and logistics problem rather than a process engineering one, and much of it can therefore be identified before financial close.

5. Loss 2: Design basis overestimation

The second loss is built into the plant on paper. If the methane yield assumed in the design is higher than the yield the plant can sustain, the shortfall appears on the first day of steady operation and never goes away.

5.1 Laboratory BMP values versus sustained full scale yield

Most designs start from the biochemical methane potential (BMP) of the feedstock, measured in batch tests. A BMP test is valuable, but it measures something specific: the approximate ultimate methane yield of a substrate, digested for a long time with an active inoculum, at good mixing and with no inhibition. Standardised protocols have been developed precisely because results vary with inoculum, test duration and reporting conventions [30]. A continuous full scale digester works under different conditions. It has a finite retention time, uneven mixing, varying feed quality and, from time to time, stress from ammonia, acids or temperature changes. It therefore recovers only part of the batch potential [17].

The fraction recovered at full scale can be estimated, and methods for doing so have been compared at European plants [15]. What is less common, particularly in Indian project reports, is any correction for it. When the BMP value is used directly as the design yield, the difference between batch potential and continuous yield becomes a permanent loss of output, and it is usually blamed on operators rather than on the

design. The correction is straightforward in principle: design yields should be taken from continuous or semi continuous digestion trials at realistic loading, or the BMP should be discounted by a realisable fraction justified for that feedstock.

5.2 Benchmark feedstock assumptions

A related error comes from the choice of reference feedstock. Cattle dung is widely used as a benchmark substrate and as a default inoculum, partly for historical reasons and partly because it is stable and buffered. Its behaviour does not represent the fibrous residues, energy grasses and high nitrogen industrial wastes that now feed most CBG plants, and in our view design assumptions carried over from dung digesters can mislead. Retention time, loading rate and nutrient balance need to be set for the actual feed, not for a convenient reference.

5.3 Feedstock characterisation failures

Design yields also go wrong when the feedstock is poorly characterised. A single sample taken during a site visit, analysed for total and volatile solids, cannot represent a supply that changes with season, storage age, mill practice or the share of soil and grit collected with the residue. In the authors' experience, plants have suffered complete shutdowns that routine feedstock analysis and testing of new feed batches would have prevented, and abrupt changes in feed composition are a well documented trigger of process upset [31]. A design basis built on one optimistic sample therefore carries two risks: an overstated yield, and an unrecognised source of later process failure.

6. Loss 3: Biological conversion and process stability

Even with sufficient feed and a realistic design yield, the digester must convert that feed reliably day after day. The third loss covers the output that is forfeited when the biology is under stress and the operator reduces loading to protect the process.

6.1 Process disturbances in agricultural digesters

Process disturbances in agricultural biogas plants have been classified by cause and by their effect on the microbial community [31]. The main categories are overloading; inhibition by ammonia, acids or hydrogen sulphide; deficiency of trace elements; and abrupt changes in feed or temperature. Each one reduces the methane yield per tonne of feed, and most of them push the operator to cut the feed rate until the process recovers. That precaution is sensible, but every day of reduced feed is a day of lost output, and recovery from a serious upset can take weeks.

6.2 Mono digestion of grasses and crop residues

Many Indian CBG plants are designed to run on a single dominant substrate: paddy straw, press mud or Napier grass. The European experience with grass silage is a warning. Long term mono digestion of grass silage was observed to fail in continuous operation, with instability linked to the substrate's nutrient composition and the absence of the buffering and trace elements that manure provides [32]. Similar mechanisms apply to straw and energy grass plants in India. A plant that runs well in its first months on a manure based inoculum may decline steadily as that inoculum washes out, unless the nutrient balance is corrected through codigestion or supplementation.

6.3 Foaming, mixing and loss of effective volume

Some biological losses are physical in origin. A survey of full scale Danish plants found that foaming was a common problem with several distinct causes, and that it frequently forced reduced loading or shutdowns [33]. Mixing is equally important. Tracer studies on large digesters have shown that a meaningful part of the reactor volume can behave as dead space, so the effective retention time is shorter than the design value [34]. Floating layers of fibre and settled layers of grit and calcium carbonate, which are common with straw and press mud, reduce the active volume further.

These losses are rarely visible on a daily log. A digester that has lost a fifth of its working volume to sediment still accepts feed and still produces gas, only at a lower yield and with less margin against overloading. The result is a slow decline that operators adapt to rather than diagnose.

6.4 Stability indicators for safe ramp up

Ramp up is where biological losses are often largest. In our experience, new plants are commonly held at reduced loading for a fixed period of about three months before being declared stable. That convention was not derived from process mechanics, and it can be either too cautious or too hasty depending on the feed and the inoculum. A composite stability index that combines several process parameters into one dynamic measure has been proposed to decide when a digester can safely move to higher loading [35]. Indicators of this kind are worth the effort, since the months lost to an unnecessarily slow or unnecessarily disrupted ramp up are a direct loss of utilisation in the years when debt service is heaviest.

7. Loss 4: Downtime and operational practice

Downtime, the output lost while part of the plant is stopped, is the most intuitive of the five losses and often the cheapest to reduce.

7.1 Feeding and preprocessing failures

In fibrous feed plants, the feeding and preprocessing line is the most common point of failure. Shredders, mixers, screw feeders and piston feeders handle abrasive, variable material, and their breakdowns stop the whole plant even when the digesters are healthy. A review of feeding systems found that the choice between continuous, semi continuous and batch feeding, and the design of the feeding equipment itself, strongly affect both process stability and plant availability [36]. A plant designed with a single feeding line and no standby equipment converts every mechanical failure into lost gas.

7.2 Instrumentation, monitoring and control gaps

Instrumentation and control of anaerobic digestion has been reviewed in depth, and the conclusion is consistent: reliable online measurement of the key process variables remains difficult and expensive, which is why many plants still rely on infrequent laboratory analysis [37]. Where closed loop feed control has been applied, it has allowed plants to run closer to their safe maximum loading [38]. In India the gap appears wider. In the authors' observation, many commercial plants have gas flow and composition meters on the upgrading unit but little process instrumentation on the digesters, and sample volatile fatty acids and alkalinity weekly or less often. Infrequent sampling allows small deviations to develop into upsets before they are detected [39].

7.3 Technical support after commissioning

India's household biogas programmes offer a lesson that the CBG sector should not have to relearn. Evaluations in Assam found that programme targets were defined by installations, and that many installed plants performed poorly or fell out of use for want of follow up support [40]. A recent field study reached a similar conclusion, attributing poor plant performance to undiagnosed feedstock, microbial and climatic problems and to the absence of a technical support system after installation [41]. Commercial CBG plants operate at a far larger scale, but many share the same structure: an EPC contractor who leaves after commissioning, an owner with little digester experience, and a thin market for experienced operators. Downtime depends not only on how often equipment fails but also on how long it takes to find someone who can diagnose the fault.

8. Loss 5: Upgrading losses, methane slip and offtake

The last loss sits between the raw biogas and the invoice. Gas that is produced but not sold contributes nothing to revenue, and gas that escapes contributes to emissions as well.

8.1 Methane slip in upgrading and gas handling

Methane losses at upgrading units have been measured at nine commercial plants in Denmark, where process losses averaged 0.81 percent of the methane fed to the upgrading unit, with water scrubbers showing the highest losses at up to about 2 percent [42]. Whole plant measurements show larger losses. Across 23 Danish biogas plants, total methane losses ranged from 0.4 to 14.9 percent of production, with a mean of 4.6 percent; agricultural plants averaged 2.4 percent, and larger plants generally lost less than smaller ones [43]. This is relevant for India, where the average functional plant is small. Each percentage point of methane lost is a percentage point of saleable output forgone and, at the same time, a direct greenhouse gas emission that erodes the climate case for the plant. No comparable programme of measurement has been published for Indian CBG plants, which means that methane slip is currently an assumption in both financial models and carbon credit claims.

8.2 Offtake, CGD connectivity and pricing

Gas that meets specification still has to be accepted. Under SATAT, most plants sell compressed gas in cascades to oil marketing company outlets or inject it into city gas networks where a connection exists [2]. When cascades are not lifted on time, when the nearest outlet cannot absorb the volume, or when grid injection is delayed, the plant must store, flare or cut production. The regulator's data show how large this loss can be. About 73 percent of CBG sold in the first half of FY 2026 to 27 travelled by cascade truck and only 14 percent by pipeline, and the regulator itself attributes low utilisation to plants located far from gas networks, plants too small to justify an individual pipeline, slow approval of pipeline grants and the absence of assured long term offtake [4]. Connected plants ran at about 65 percent of rated capacity against about 40 percent for the rest [4]. Part of that difference may reflect plant size and management as well as connectivity, but the gap is too large to ignore. The Standing Committee also noted that pricing pegged to CNG leaves thin margins that do not reflect feedstock costs [6]. The blending obligation, mandatory since FY 2025 to 26 [3], has raised demand, yet blending still fell short of the obligation in both reporting periods [4, 7]. Offtake loss is therefore partly a market problem and partly a question of plant location and logistics, and both should be settled before construction.

9. Synthesis: ranking the losses

9.1 Relative magnitude and uncertainty of each loss

Without plant level data, the five losses cannot yet be ranked with numbers. They can, however, be ranked by the strength of the evidence behind them, by their likely contribution and by how far a developer can control them. Table 4 does this, drawing on the literature reviewed above and on the authors' plant experience. The judgements are deliberately conservative and should be read as hypotheses for measurement rather than conclusions.

Table 4. Qualitative assessment of the five losses for commercial CBG plants in India. Likely contribution is the authors' judgement from the reviewed evidence and plant experience, to be tested against measured data.

Loss	Strength of evidence in India	Likely contribution	Controllability	Data most needed
L1 Feedstock	Moderate: policy and supply studies, no plant data	High, especially for seasonal residues	High before financial close, low after	Monthly feed received against design; storage losses
L2 Design basis	Weak: mostly practitioner reports	High where BMP is used directly	High at design stage	Yield in a stable reference period against design yield
L3 Biological	Weak in India; strong internationally	Moderate, higher for mono digestion	Moderate, through feed and nutrient management	Loading, VFA to alkalinity ratio, yield trend
L4 Downtime	Weak in India; moderate internationally	Moderate	High, through design redundancy and support	Operating hours, stops, repair times
L5 Upgrading and offtake	Moderate for offtake (regulator data); none for slip	High for plants without pipeline access; slip low to moderate	Moderate; mostly fixed by site choice	Gas offered against accepted; recovery; slip

Three losses stand out. Feedstock availability and design basis overestimation are both likely to be large, and both are largely decided before the plant is built. The regulator's data add a third: offtake, which on the reported difference between connected and unconnected plants may account for a large share of the national gap [4], and which is also fixed largely by the choice of site. A substantial part of the utilisation gap is therefore locked in at the feasibility stage, by documents that lenders and approving agencies review. Biological and downtime losses are smaller in a well run plant but can become severe in a poorly run one, and they are the losses that operators are usually blamed for. Methane slip is probably small in output terms, but it is unmeasured in India, and its importance for carbon accounting is out of proportion to its share of lost output.

9.2 Interactions between losses

The framework treats the losses as sequential, but in practice they feed on each other. A feedstock shortfall often leads operators to substitute whatever material is available, and an abrupt change in feed is one of the classic triggers of process upset [31]. A feeding system failure leaves the digester underfed for days, and the attempt to make up lost production afterwards can overload it. A design yield set too high leads operators to push loading in search of the promised output, which raises the risk of instability. Poor segregation of municipal waste adds grit that reduces active volume, which then appears as a biological loss. Because of these links, the order in which losses are corrected matters. In most cases feedstock security and a realistic design basis should come first, since they remove the pressures that cause many of the downstream problems.

9.3 Comparison of Indian and international experience

Germany and China offer contrasting reference points. In the year round monitoring study, the German plants, which operate within a mature ecosystem of specialised service providers and laboratories, departed less from their design values than the Chinese plants [14], and the German fleet as a whole ran at roughly 70 to 80 percent of its potential [16], against 44 percent for Indian CBG plants [4]. China's rural biogas programme expanded rapidly on capital subsidies and installation targets, and a large share of its plants ended up underused [9]. In its incentives, India's CBG sector sits closer to the Chinese pattern, since programme targets are still framed in terms of plants commissioned, although the regulator's new utilisation reporting is a

welcome step [4]. In its commercial structure it sits closer to the German pattern, with private owners who carry the financial consequences of poor performance [5]. Owners who bear the cost of the gap have every reason to measure it, provided the sector gives them the tools and the incentive to do so.

10. Implications and recommendations

10.1 For developers and EPC contractors: correcting the design basis

For developers, the framework turns a vague risk into a checklist. Feedstock plans should show contracted supply by month, with storage sized for the lean season and storage losses included. Design yields should come from continuous trials or from BMP values discounted by a realisable fraction justified for that feed. Feeding and preprocessing lines should include standby equipment for the components most likely to fail. Ramp up should follow measured stability indicators rather than a fixed calendar. These measures are familiar individually; the framework adds a way to value each one in output terms, so that capital goes where it closes the largest part of the gap.

10.2 For lenders: utilisation based due diligence

Techno economic studies of residue based CBG already show that project viability is highly sensitive to utilisation [12]. Lenders can use the five stages as a structure for due diligence: asking for evidence on each stage separately rather than accepting a single nameplate output, and testing debt service at a sustained utilisation well below nameplate in the first years of operation. The effect on debt service is larger than the effect on revenue. Revenue falls roughly in proportion to utilisation, but operating costs for staff, power, maintenance and insurance fall much less, so operating cash flow, and with it the debt service coverage ratio, falls faster than output. A conservative base case that assumes gradual ramp up and an explicit feedstock risk margin is more likely to match reality than one that assumes full output from the second year.

10.3 For policymakers: from installation targets to sustained output

The Standing Committee recommended that incentives move from capital support towards generation based support [6], and the logic of this review supports that recommendation. Policy that rewards gas delivered, rather than plants commissioned, aligns the interests of developers, lenders and government around the same number. The regulator's half yearly reporting of utilisation [4] is a strong start; extending it to plant level data by feedstock, size and state would let developers and lenders learn from the whole fleet. Earlier barrier studies identified institutional and market barriers as central to the slow growth of biogas in India [10], and a transparent record of actual output would address both by giving investors the performance history they currently lack. Table 5 brings the recommendations together by stakeholder and by the loss stage each one addresses.

Table 5. Summary of recommendations by stakeholder and the loss stage each addresses.

Stakeholder	Recommendation	Loss addressed
Developers	Contract feedstock by month and size storage for the lean season, including storage losses	L1
Developers and EPC contractors	Set design yields from continuous trials or discounted BMP; characterise feed across seasons	L2
Operators	Correct nutrient balance in mono digestion; manage grit and floating layers; ramp up on stability indicators	L3
EPC contractors	Provide standby feeding and preprocessing equipment; agree post commissioning support	L4
Developers and buyers	Settle offtake logistics before construction; measure methane slip	L5
Lenders	Assess each stage separately; test debt service at conservative utilisation	All
Policymakers	Reward delivered gas; publish plant level output alongside capacity	All

10.4 A minimum monitoring dataset for Indian CBG plants

None of these steps works without measurement. Table 6 proposes a minimum dataset that a commercial CBG plant could record with modest instrumentation and a basic laboratory, and that would allow each of the five losses to be calculated. Most of the items are already logged at well run plants. The difference is that they need to be recorded consistently, kept for the life of the plant and analysed against the design basis. Composite stability indicators [35] and structured monitoring practice [39] provide a starting point for the process variables.

Table 6. Proposed minimum monitoring dataset for calculating the five losses at a commercial CBG plant.

Parameter	Purpose	Frequency	Loss stage
Feedstock received and fed, by type (t)	Available capacity against design	Daily	L1
TS and VS of each feed and of stored material	Feed quality and storage loss	Weekly and per batch	L1, L2
Raw biogas flow and methane content	Specific methane yield at full scale	Continuous	L2, L3
VFA, alkalinity, pH, ammonium nitrogen	Process stability	Two to three times a week	L3
Digester temperature and mixing hours	Process conditions and effective volume	Continuous	L3
Sediment depth or tracer test	Loss of active volume	Annually	L3
Operating hours and unplanned stops by equipment	Availability and downtime causes	Daily	L4
Upgrading inlet and product flow, off gas methane	Upgrading recovery and slip	Continuous and quarterly	L5
Gas flared and gas offered against accepted	Offtake loss	Daily	L5

11. Research gaps and future directions

The review points to five gaps that limit how well the utilisation problem can be understood and managed.

First, national utilisation is now reported [4], but no plant level dataset by feedstock, size or region has been published. The single measured case in this review shows how much one plant's records can reveal; an anonymised dataset covering a few dozen plants over two or three years would allow the framework to be calibrated and the losses to be ranked with numbers rather than judgement.

Second, the realisable fraction of BMP at full scale has not been established for the main Indian feedstocks, namely paddy straw, press mud, Napier grass and segregated municipal organic waste. Paired studies that measure both batch potential and continuous full scale yield on the same feed would remove one of the largest uncertainties in project design.

Third, storage losses for baled straw, heaped press mud and ensiled grass under Indian climatic conditions are almost unmeasured. Temperate studies report dry matter losses of 5 to 17 percent for stored bales [24, 25]; because seasonal feedstocks in India spend most of the year in storage, often through the monsoon, local losses could be higher and could be among the largest hidden contributors to the gap.

Fourth, methane slip and fugitive emissions at Indian CBG plants have not been measured in any published study. That is a gap for plant economics and a larger one for the credibility of carbon credits.

Fifth, the sector lacks agreed performance indicators. A standard set, along the lines of the European benchmarking work [13], adopted by oil marketing companies, lenders and industry associations, would allow plants to be compared fairly and would give the market the information it needs to price risk.

A practical route to closing these gaps is a staged validation of the framework. One or two operating plants with different feedstocks would record the dataset in Table 6 for at least a full year, including a lean season. Over that year, the five losses would be calculated monthly, the stage definitions tested for double counting, and the results compared with the plant's design basis. Extending the exercise to a small group of plants through an industry association would then provide the first measured benchmark of capacity utilisation for Indian CBG.

12. Conclusions

India's CBG programme has moved from policy ambition to a growing fleet of operating plants, supported by a guaranteed buyer and, from FY 2025 to 26, a blending obligation. Its success will be judged less by the number of plants commissioned than by the share of their capacity that turns into gas sold. The regulator's latest figures put that share at 44 percent across 210 functional plants in the first half of FY 2026 to 27 [4], and the reasons, on the evidence reviewed here, are both foreseeable and measurable.

The loss decomposition framework proposed here allows that shortfall to be traced stage by stage. Because each loss acts on the output left by the one before, moderate shortfalls compound, and the evidence suggests that feedstock security, optimistic design yields and offtake logistics, all fixed largely before construction, account for much of the gap. Operating practice and support govern the biological and downtime losses, while methane slip remains unmeasured in India.

The most important practical step is to start measuring. A minimum monitoring dataset, recorded consistently and analysed against the design basis, would let developers target their capital, let lenders price risk on evidence and let policymakers reward the gas that is actually delivered. Closing the utilisation gap will not need new technology so much as better information about the plants that already exist.

Declarations

Declaration of competing interest. The authors are partners in an engineering consultancy that advises developers of CBG plants, and several of the cited works are their own publications. The authors declare no

other competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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