Biomethane Production, Upgrading, and Use from a Systems Perspective

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This review examines the biomethane value chain from feedstock selection and feedstock-specific pretreatment to digester operation, gas upgrading, utilization pathways, and life-cycle constraints. Rather than evaluating biomethane by methane purity alone, it emphasizes the combined effects of feedstock quality, pretreatment intensity, process stability, upgrading energy demand, methane slip, digestate management, and end-use infrastructure. Key anaerobic digestion variables, including temperature, pH, volatile fatty acids, carbon-to-nitrogen ratio, organic loading rate, hydraulic retention time, and inhibitor control, are linked to process robustness. Major upgrading technologies, including water scrubbing, chemical absorption, pressure swing adsorption, membrane separation, and cryogenic separation, are compared in terms of methane purity, methane loss, energy demand, cost tendency and deployment fit. Biomethane shows the strongest mitigation potential when wastes are locally sourced, methane losses are controlled and digestate is safely recycled.

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INTRODUCTION

Biomethane (Bio-natural Gas, BNG) is an upgraded methane-rich gas derived from raw biogas. Raw biogas is produced when microorganisms decompose organic matter under anaerobic conditions. It typically contains CH_4 (50% to 75% by volume), CO_2 (20% to 50%), and smaller amounts of H_2S, NH_3, N_2, water vapor and volatile organic compounds (Braun 2007; Morgan *et al.* 2018). Siloxanes are mainly associated with landfill gas, municipal solid waste, and sewage-sludge digestion, where they originate from silicone-containing consumer and industrial products rather than from clean agricultural biomass. During combustion, these compounds can form abrasive SiO_2 deposits that damage engines and downstream equipment.

Raw biogas requires purification and upgrading before high-value use. CO_2 reduces calorific value, while H_2S, moisture and siloxanes can cause corrosion, freezing, solvent degradation or engine damage (Hagen *et al.* 2001). After upgrading, BNG commonly exceeds 95% CH_4 and can approach the composition and heating value of fossil natural gas. This makes it suitable for grid injection, heat and power generation, and transport-fuel applications when local quality standards are met (Ullah Khan *et al.* 2017; Shah *et al.* 2024).

BNG is strategically relevant because it connects renewable energy production with organic-waste management. It can reduce dependence on fossil natural gas, recover energy from manure, food waste, sewage sludge, crop residues and high-strength organic wastewater, and produce digestate that can return nutrients to soil (Scarlat *et al.* 2018; Archana *et al.* 2024; Guan *et al.* 2024). Its climate value, however, should be described cautiously. BNG is better framed as a low-carbon or potentially near-carbon-neutral energy carrier than as an inherently carbon-neutral fuel. Net mitigation depends on feedstock type, avoided emissions from alternative waste management, methane leakage, methane slip during upgrading, energy demand, digestate handling, and the selected system boundary (Rehl and Müller 2011; Singlitico *et al.* 2019; Kolb *et al.* 2021; Ardolino *et al.* 2021).

BNG production and utilization have expanded with renewable-gas policy, waste-management demand and gas-grid decarbonization. Europe has been a leading region in biomethane production, grid injection, and transport-fuel use. By the end of 2018, 610 biomethane plants were operating in Europe (EBA 2020). The global biomethane market was estimated at USD 620 million in 2017 and projected to reach USD 4.96 billion by 2026 (Hoo *et al.* 2020). North America also has a large biogas base, especially from wastewater treatment and landfills. In Asia, China has substantial biogas potential from agricultural and organic wastes (Scarlat *et al.* 2018). Despite this momentum, high upgrading cost, methane-loss control, policy continuity and market access remain major constraints (Sun *et al.* 2015; Awe *et al.* 2017).

Previous reviews have advanced the understanding of pretreatment, anaerobic digestion (AD) optimization and upgrading technologies. Many, however, still treat these steps separately. This limits evaluation of how feedstock properties, reactor design, upgrading choice, and final use interact across the BNG value chain. This review therefore adopts a systems-integration perspective. It evaluates BNG as a linked chain connecting feedstock quality, pretreatment severity, digester configuration, upgrading technology, methane-slip control, digestate management and end-use requirements (Ardolino *et al.* 2021; Bakkaloglu and Hawkes 2024; Galloni and Di Marcoberardino 2024; Hidalgo and Martín-Marroquín 2025; Yamaji *et al.* 2024).

Within this framework, BNG pathways are assessed through five coupled dimensions: resource compatibility, process robustness, energy-carbon performance, economic-scale fit, and infrastructure fit. These dimensions explain why technology choices vary with gas composition, plant scale, heat availability, grid or transport-fuel specifications, and opportunities to valorize digestate or biogenic CO_2. The review therefore avoids ranking upgrading technologies by CH_4 purity alone. Instead, it considers purity, methane loss, energy demand, cost tendency and life-cycle implications together (Cavaignac *et al.* 2021; Ardolino *et al.* 2021; Ammenberg *et al.* 2024).

FEEDSTOCKS AND PRETREATMENT FOR BIOMETHANE PRODUCTION

Feedstock Categories and Production Potential

Agricultural residues, especially animal manure, crop straw, and grass resources, are major substrates for sustainable biogas production. They are widely available and generally do not directly compete with food production (Commission 2014). In Europe, the potential of animal manure, straw, and permanent-crop pruning residues has been estimated at 4.4×10^3 PJ by 2030 (Meyer *et al.* 2018). Manure can support nutrient recycling and reduce CH_4 and N_2O emissions compared with conventional storage, but its high moisture content and relatively low energy density can limit standalone economics. Crop residues provide larger lignocellulosic resources, but their recalcitrant structure often requires pretreatment (Scarlat *et al.* 2018).

Food waste (FW) and high-concentration organic wastewater (HCOW) provide readily degradable feedstocks. FW has high energy density and biodegradability, which can support high theoretical CH_4 yields (Lin *et al.* 2013; Paritosh *et al.* 2017). HCOW from paper, brewing, food-processing, and pharmaceutical industries contains high chemical oxygen demand and can be suitable for anaerobic digestion (AD). A bottom-up estimate placed China's BNG potential from HCOW at approximately 5.59 billion m^3 in 2021, with paper wastewater contributing the largest share (Wang *et al.* 2025).

Microalgae are attractive because they can grow rapidly, use wastewater or atmospheric CO_2, and avoid direct competition with arable land (Zabed *et al.* 2020). Their digestion performance depends on species, cultivation conditions, and pretreatment. Fresh or protein-rich microalgae often have low C/N ratios, which can increase ammonia release during mono-digestion. Carbohydrate-rich, lipid-rich or nutrient-limited cultures may behave differently. C/N limitations should therefore be treated as feedstock- and process-dependent, and co-digestion with carbon-rich substrates is often used to improve nutrient balance (Yen and Brune 2007; Ward *et al.* 2014; Solé-Bundó *et al.* 2019).

Lignocellulosic biomass is abundant, but cellulose and hemicellulose are protected by lignin. This structure limits microbial access and makes hydrolysis a common rate-limiting step in AD (Tisma *et al.* 2017; Yu *et al.* 2019). Pretreatment is therefore central to improving the biogas potential of straw, pruning residues, and other lignocellulosic feedstocks (Kumar *et al.* 2021).

Feedstock-specific Pretreatment Strategies

Pretreatment should be selected according to feedstock constraints rather than applied as a generic yield-enhancement step. Manure and HCOW usually require equalization, homogenization, and inhibitor control. FW often needs size reduction, pulping, contaminant removal, and buffering because it acidifies rapidly. Lignocellulosic residues require physical, chemical, biological or combined pretreatments to weaken the lignin-cellulose barrier. Microalgae may require cell disruption or co-digestion, but harvesting and dewatering energy can offset digestion gains (Passos *et al.* 2014; Xu *et al.* 2018; Yu *et al.* 2019; Ahlberg-Eliasson *et al.* 2021).

Physical pretreatments reduce particle size, increase surface area, and improve contact between substrates, enzymes, and microorganisms. Thermal and hydrothermal pretreatments can disrupt biomass structures under controlled temperature and pressure. Pyrolysis should not be presented as a routine AD pretreatment, because it is primarily a thermochemical conversion route for biochar, bio-oil and syngas. It is relevant to AD only when discussed as part of an integrated biochar-AD strategy.

Chemical pretreatments can improve hydrolysis but may introduce inhibitors or environmental burdens. Alkaline treatment disrupts lignin and increases cellulose accessibility. For example, alkaline H_2O_2 treatment of agave bagasse increased biogas yield by 150% to 360% in one study (Galindo-Hernández *et al.* 2018). Biological pretreatment uses fungi or enzymes to degrade lignin or hemicellulose under mild conditions, but treatment times can be long (Tisma *et al.* 2017). The preferred pretreatment is therefore the least intensive option that improves biodegradability without excessive energy input, high cost, or inhibitor formation.

Co-digestion for Nutrient Balance and Stability

Anaerobic co-digestion (AcoD) mixes two or more substrates to improve C/N ratio, buffering capacity, nutrient balance, and inhibitor dilution (Mata-Alvarez *et al.* 2014). It is particularly useful when mono-digestion is constrained by ammonia from high-nitrogen manure, rapid acidification from FW, or nutrient imbalance in carbon-rich residues.

Combining manure with straw, FW or other carbon-rich substrates can move the mixture toward the commonly recommended C/N range of 20 to 30. This supports microbial balance and improves tolerance to loading shocks. Reported examples include pig manure and corn straw co-digestion with CH_4 production of 403.9 mL/g VS (Arias *et al.* 2020) and FW-sludge co-digestion with improved CH_4 yield and dewatering performance (Liu *et al.* 2012). Ratio optimization should account for feedstock composition, biodegradability, buffering capacity, methane potential, and post-mixing interactions. Experimental designs or kinetic models are often needed because apparently favorable substrates can still produce inhibitory mixtures (Sosnowski *et al.* 2008).

ANAEROBIC DIGESTION TECHNOLOGIES AND PROCESS OPTIMIZATION

Fundamental Principles of Anaerobic Digestion

Anaerobic digestion (AD) is usually described as four coupled biochemical steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Kumar and Samadder 2020; Archana *et al.* 2024). These steps can occur simultaneously in single-stage reactors or be separated in multi-stage systems. Figure 1 summarizes the main conversion steps and microbial groups.

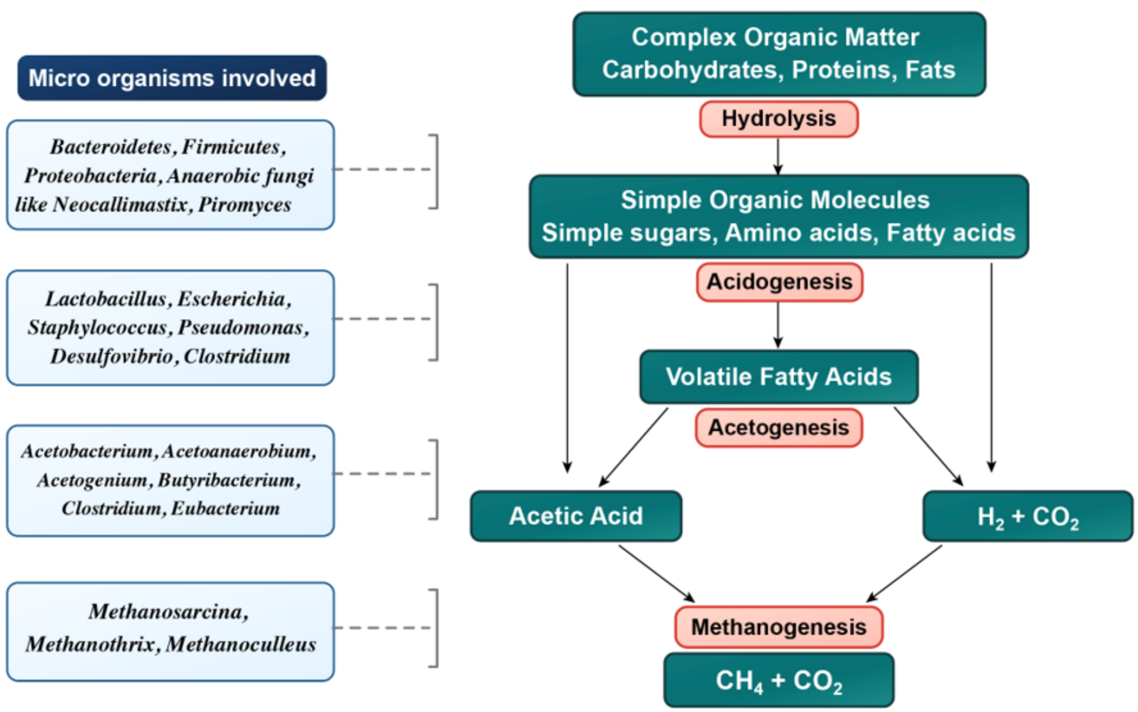

Fig. 1. Four steps in anaerobic digestion of waste products with the list of microorganisms involved in each step. (Reprinted with permission from Elsevier; Archana *et al.* 2024)

Hydrolysis is often rate-limiting when substrates contain complex polymers such as lignocellulose (Mahmudul *et al.* 2021). Extracellular enzymes convert insoluble macromolecules into soluble monomers. Acidogenic microorganisms then transform these products into volatile fatty acids (VFAs), alcohols, H_2 and CO_2. Acetogenic bacteria further convert these intermediates into acetate, H_2, and CO_2. Methanogenic archaea finally produce CH_4 through acetoclastic methanogenesis from acetate or hydrogenotrophic methanogenesis from H_2 and CO_2. Stable AD depends on balanced microbial activity across these steps and on operating conditions that prevent intermediate accumulation.

Key Influencing Factors

AD performance is governed by coupled operating variables rather than by single optimum values. Temperature, pH, VFAs, C/N ratio, ammonia, toxic substances, organic loading rate (OLR), and hydraulic retention time (HRT) should be interpreted together.

Temperature

AD is commonly operated under psychrophilic (~20 ℃), mesophilic (~35 ℃), or thermophilic (~55 ℃) conditions. Mesophilic digestion is widely adopted because it often provides greater stability, lower VFA-accumulation risk, and lower net energy demand than thermophilic operation (Mao *et al.* 2015). Thermophilic conditions can accelerate hydrolysis and methane formation, but they can also increase free-ammonia toxicity and destabilize poorly buffered systems. Temperature effects should therefore be evaluated with alkalinity, ammonia concentration, OLR and microbial adaptation (Chen *et al.* 2008; Mao *et al.* 2015).

pH and volatile fatty acids (VFA)

Reactor pH reflects the balance between acid production, ammonia release, and buffering capacity. Acidogenic bacteria generally favor pH 5.5 to 6.5, while methanogens perform best near neutral to mildly alkaline conditions. In mixed AD systems, pH 6.8 to 7.2 is often reported as favorable (Rodrigues *et al.* 2025). VFA accumulation indicates that acid formation exceeds conversion by acetogens and methanogens. Because acceptable VFA levels vary with reactor type, substrate and acclimation, VFA should be interpreted with alkalinity. The VFA/alkalinity ratio or the intermediate alkalinity/partial alkalinity ratio can provide earlier warning than pH alone (Martín-González *et al.* 2013; Sun *et al.* 2019). Practical pH control relies on sufficient carbonate/bicarbonate buffering, alkaline addition, co-digestion, stepwise feeding and OLR management. Online pH monitoring is useful, but it can respond slowly during early acidification. Combined monitoring of VFAs and alkalinity gives a more sensitive indication of process imbalance (Chen *et al.* 2015a; Gonde *et al.* 2023).

C/N ratio

The C/N ratio indicates substrate nutrient balance. Excessively high C/N can cause nitrogen deficiency, while low C/N can increase ammonia inhibition. A C/N range of 20 to 30 is commonly used as a practical guideline, but it should not be treated as a universal optimum. Suitable values depend on feedstock composition, biodegradability, nitrogen form, buffering capacity, inoculum adaptation, and co-digestion strategy (Mata-Alvarez *et al.* 2000; Mao *et al.* 2015).

Ammonia and other inhibitors

Ammonia is required for microbial growth, but free ammonia can inhibit methanogenesis at elevated concentrations. Its toxicity increases with pH and temperature (Rodrigues *et al.* 2025). Mitigation options include dilution, co-digestion, ammonia stripping, chemical precipitation, and trace-element addition, selected according to the cause and severity of inhibition (Mao *et al.* 2015). Sulfides, alkali and alkaline-earth metals, long-chain fatty acids, and oxygen exposure can also inhibit methanogens or corrode equipment (Kumar and Samadder 2020).

Treatment-train design

Some substrates and effluents require stabilization beyond methane recovery. AD can be followed by aerobic polishing, activated-sludge treatment, or composting/ maturation to reduce residual COD, odors and digestate instability. These combined systems can improve effluent or digestate quality, but they add aeration demand, operational complexity and cost. Their use should be justified by discharge limits, digestate standards, and final product requirements (Chan *et al.* 2009; Lu and Xu 2021).

Organic loading rate (OLR) and hydraulic retention time (HRT)

OLR and HRT define the balance between throughput and conversion. Higher OLR can increase treatment capacity within the stable range, but excessive loading can trigger acidification. HRT must be long enough for substrate degradation and microbial retention, but unnecessarily long HRT lowers volumetric productivity (Xu *et al.* 2018). In CSTR systems, short HRT can cause VFA accumulation and substrate washout; longer HRT or two-stage digestion can mitigate these risks (Kumar and Samadder 2020).

Reactor Configurations

Reactor selection depends on substrate composition, solids content, desired loading rate, microbial retention, and operational mode. The main reactor types are shown in Fig. 2.

Continuous stirred tank reactor (CSTR)

The CSTRs are simple and widely used for liquid manure, FW slurry, and organic industrial wastewater. Their advantages include continuous operation and uniform mixing. Their disadvantages include relatively long HRT, heating, and mixing energy demand, and possible microbial washout with effluent. Reported performance depends strongly on substrate and operating conditions (Kumar and Samadder 2020).

Upflow anaerobic sludge blanket (UASB)

The UASB reactors are suitable for soluble organic wastewater, including industrial and municipal streams. Granular sludge retains high microbial concentrations and enables high organic removal rates at shorter HRTs (Mullai *et al.* 2025). Internal circulation and expanded granular sludge bed designs further improve mass transfer and shock-load tolerance.

Anaerobic sequencing batch reactor (ASBR)

The ASBRs operate through sequential filling, reaction, settling, drainage, and idle phases in one tank. This configuration can provide flexible control for low-flow or variable wastewater streams (Xu *et al.* 2018).

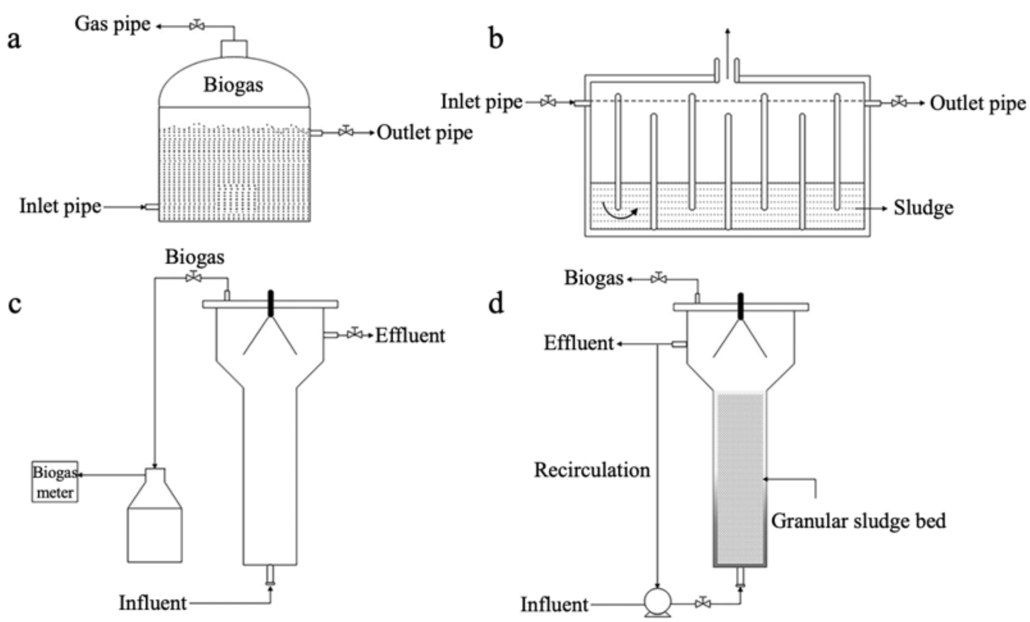

Fig. 2. Schematic representation of: a) biodigester configuration, b) conventional ABR configuration, c) UASB configuration, and d) EGSB configuration (Reprinted with permission from Taylor & Francis, Rodrigues *et al.* 2025)

Anaerobic baffled reactor (ABR)

The ABRs divide the reactor into compartments with vertical baffles. This promotes partial separation of acidogenesis and methanogenesis, improves solids retention and increases tolerance to hydraulic or organic shocks.

Two-stage/multi-stage systems

Multi-stage systems separate hydrolysis-acidification from methanogenesis. This can improve stability for rapidly degradable substrates that acidify single-stage reactors. Reported benefits include higher CH_4 yield, better reliability, improved pathogen control and greater volatile-solids removal (Karthikeyan *et al.* 2024). Temperature-phased AD is one example, combining thermophilic and mesophilic stages (Rodrigues *et al.* 2025).

Enhancement Strategies

AD enhancement strategies include pretreatment, co-digestion, additives, and bioelectrochemical integration. Pretreatment mainly improves hydrolysis and substrate accessibility for lignocellulose and microalgae, but its benefit must exceed added energy demand, cost, and inhibitor risk (Ao *et al.* 2024; Siddique and Wahid 2018; Kumar and Samadder 2020).

Co-digestion enhances AD by balancing nutrients, diluting inhibitors and increasing buffering capacity. It is especially relevant for FW, which can acidify rapidly unless buffered by manure, sludge, or other co-substrates (Mishra *et al.* 2021; Vasco-Correa *et al.* 2018).

Additives can support microbial activity under specific conditions. Biochar may improve microbial attachment, mitigate inhibitors and facilitate electron transfer (Mishra *et al.* 2021). Zero-valent iron, trace elements, and nutrient additives can also support methanogenesis, but inappropriate dose or substrate mismatch can reduce CH_4 yield or increase cost (Karthikeyan *et al.* 2024). Microbial electrolysis cell integration can promote electron transfer and in-situ upgrading, but it remains more complex than conventional AD operation (Ao *et al.* 2024).

Biogas Purification and Upgrading Technologies

Biogas treatment involves two linked steps. Purification removes harmful impurities such as H_2S, water vapor, and siloxanes. Upgrading separates CO_2 to increase CH_4 purity for grid injection, transport fuel or other high-value uses (Ryckebosch *et al.* 2011).

Impurity Removal before Upgrading

H_2S is corrosive and toxic, and its concentration varies with feedstock sulfur content. Removal options include chemical absorption, adsorption, and biological filtration (Bauer *et al.* 2013a). Adsorbents such as iron oxides, activated carbon, and zeolites are widely used, while biological filters oxidize H_2S to elemental sulfur or sulfate with comparatively low operating cost (Khoshnevisan *et al.* 2017). H_2S control is particularly important before amine-based CO_2 separation because sulfur compounds can degrade or poison solvents (Muñoz *et al.* 2015).

Water vapor can condense or freeze in pipelines and equipment. It is usually removed by condensation, cooling, or adsorption drying. Siloxanes form silica during combustion and can damage engines. Their removal relies mainly on activated carbon or specialized zeolites, whereas biological filtration is not a primary siloxane-control method (Ryckebosch *et al.* 2011; Montanari *et al.* 2010; Golmakani *et al.* 2022). NH_3 and halogenated hydrocarbons may require digester-level control or activated-carbon polishing. The purification train should be matched to gas source, impurity profile and downstream upgrading technology (Sun *et al.* 2015).

Main Carbon Dioxide Separation Technologies

CO_2 separation raises CH_4 concentration so that the gas can meet Wobbe index and end-use standards (Angelidaki *et al.* 2018). The main technology families are absorption, adsorption, membrane separation, and low-temperature separation.

Water scrubbing exploits the higher solubility of CO_2 than CH_4 in water. Compressed biogas contacts countercurrent water in a packed column, CO_2 is absorbed, and CH_4-rich gas exits from the top. Flashing and stripping recover dissolved CH_4 and regenerate water. Organic solvents offer higher CO_2 solubility but increase solvent cost. Chemical absorption uses amines or alkaline solutions and can achieve high CH_4 purity, but solvent regeneration requires heat and H_2S must be removed upstream (Ryckebosch *et al.* 2011; Adnan *et al.* 2019).

Pressure swing adsorption (PSA) uses zeolites, activated carbon, or other adsorbents to selectively adsorb CO_2 under pressure. Cycles of pressurization, adsorption, depressurization, and regeneration allow continuous operation (Bauer *et al.* 2013a). Metal-organic frameworks show high CO_2 adsorption capacity, but many remain at experimental or early demonstration stages (Golmakani *et al.* 2022).

Membrane upgrading relies on differential gas permeability. CO_2 preferentially permeates through the membrane while CH_4 is retained. Multi-stage systems with recycle can improve purity and recovery. Membranes offer modularity and relatively low energy demand, but they require reliable pretreatment because H_2S, moisture condensation, and siloxanes can reduce membrane performance (Chen *et al.* 2015b).

Table 1. Comparison of Major Biogas Upgrading Technologies

Method	CH_4 purity (%)	CH_4 loss (%)	Energy demand (kWh/Nm^3 raw biogas)	CAPEX (EUR/Nm^3/h raw biogas)	OPEX tendency	Sources
Water scrubbing	96 to 98	1 to 4	0.16 to 0.30 electricity; up to approximately 0.45 with extended compression or cooling boundaries	1500 to 2200	Low to medium; depends on water circulation, compression and off-gas treatment	(Bauer *et al.* 2013b; Galloni and Di Marco-berardino 2024)
Organic solvent scrubbing	96 to 98	0.5 to 1.5	0.20 to 0.50 electricity, depending on regeneration, thermal oxidation and drying boundaries	1500 to 2200	Medium; solvent circulation and regeneration dependent	(Bauer *et al.* 2013b; Galloni and Di Marco-berardino 2024)
Chemical scrubbing	97 to 99.8; often >99	<0.1 to 0.5	Approximately 0.60 to 0.76 combined electricity and regeneration heat	1600 to 2300	Medium–High: regeneration heat, solvent management, corrosion control, and H_2S pretreatment.	(Bauer *et al.* 2013b; Adnan *et al.* 2019, Galloni and Di Marco-berardino 2024)
PSA	96 to 99	1.8 to 4	0.20 to 0.34 electricity; up to approximately 0.45 when drying, final compression or tail-gas treatment is included	1500 to 2100	Medium; compression, adsorbent regeneration and methane recovery dependent	(Bauer *et al.* 2013b; Galloni and Di Marco-berardino 2024; Golmakani *et al.* 2023)
Membrane	97 to 99.9	0.5 to 2	0.20 to 0.50 electricity, depending on stage number, recycle, purity target and compression boundary	1400 to 2000	Low to medium; membrane replacement and compression dependent	(Bauer *et al.* 2013b; Chen *et al.* 2015b; Galloni and Di Marco-berardino 2024)
Cryogenic	97 to 99+	0.5 to 3	Approximately 0.51 electricity in one 1000 Nm^3/h raw-biogas case; higher when liquefaction is included	Approximately 2300 in one 1000 Nm^3/h case	High and boundary-sensitive, especially with bio-LNG or high-purity CO_2 recovery	(Yousef *et al.* 2018; Galloni and Di Marcoberardino 2024; Hidalgo and Martín-Marroquín 2025)

Note: Energy-demand values are normalized, where possible, to Nm^3 of raw biogas entering the upgrading unit. For chemical absorption, electricity and regeneration heat are reported together because heat may be supplied by waste heat or external heat and is not directly equivalent to electricity. CAPEX values are indicative and vary with plant scale, redundancy, gas pretreatment, off-gas treatment, biomethane compression and local construction conditions. OPEX is reported qualitatively because the cited literature uses inconsistent system boundaries. Cryogenic values are especially boundary-sensitive because some studies report energy per kg CH_4 or per kg liquid biomethane. These values should therefore be interpreted as technology-selection indicators rather than supplier guarantees.

Cryogenic separation uses differences in phase behavior between CH_4 and CO_2. Biogas is compressed and cooled so that CO_2 can be condensed or solidified, while CH_4 is recovered as high-purity gas or liquid biomethane. Cryogenic systems can also recover high-purity biogenic CO_2, but their energy demand and cost are strongly boundary-dependent (Yousef *et al.* 2018).

Quantitative Comparison and Technology Selection

Upgrading technologies differ in CH_4 purity, CH_4 loss, energy demand, capital intensity, operating-cost drivers, and fit with end-use specifications. Selection should consider feed-gas composition, plant scale, impurity profile, methane-slip control, heat and power availability, gas-grid requirements, transport-fuel standards, bio-LNG production and biogenic CO_2 recovery.

UTILIZATION PATHWAYS AND SYSTEM INTEGRATION

Energy Applications

BNG can substitute for fossil natural gas when it meets the required CH_4 purity, heating value and impurity limits. Grid-quality biomethane typically contains more than 95% CH_4 and can reach heating values comparable to conventional natural gas (Maghanaki *et al.* 2013). Main applications include combined heat and power (CHP), bio-compressed natural gas (bio-CNG), bio-liquefied natural gas (bio-LNG), gas-grid injection, and boiler or residential fuel.

CHP uses BNG in internal combustion engines, gas turbines, Stirling engines, or fuel cells to generate heat and electricity. Gas engines commonly reach electrical efficiencies of 35% to 40%, while solid oxide fuel cells can reach higher conversion efficiencies under suitable conditions (Ullah Khan *et al.* 2017). CHP is most attractive when heat can be used locally, because wasted heat reduces the system benefit (Sawatdeenarunat *et al.* 2016).

Transport-fuel use is a second major pathway. BNG can be compressed as bio-CNG or liquefied as bio-LNG. Sweden has been an early adopter, with 54% of its BNG production upgraded to vehicle fuel in 2013 (Larsson *et al.* 2016). Reported climate benefits depend on vehicle baseline, feedstock, upgrading energy, and methane leakage. Therefore, transport claims should be reported on a life-cycle basis rather than from tailpipe CO_2 alone (Golmakani *et al.* 2023; Mullai *et al.* 2025).

Gas-network injection enables spatial separation between production and final use. Once BNG meets local gas-quality standards, it can use existing pipeline infrastructure for long-distance distribution. This pathway improves market access but imposes strict limits on CH_4 content, Wobbe index, H_2S, moisture, oxygen, and other impurities. The value of grid injection therefore depends as much on infrastructure compatibility and regulation as on upgrading performance.

Methanation and Carbon Dioxide Integration

Beyond conventional upgrading, biological methanation can convert the CO_2 fraction of biogas into additional CH_4 using H_2. This route is relevant to a systems-integration perspective because it links AD, renewable electricity, electrolysis, and gas-grid storage. It should be distinguished from broader chemical conversion routes, which require separate catalysts, syngas platforms or downstream chemical markets and are outside the main scope of this review.

In conventional AD, H_2 is generated as a short-lived intermediate during acidogenesis and acetogenesis. It is rapidly consumed through interspecies H_2 transfer, and stable digestion requires hydrogenotrophic methanogens to maintain low H_2 partial pressure. If H_2 accumulates, syntrophic oxidation of propionate, butyrate, and other reduced intermediates becomes less favorable, slowing VFA conversion and threatening process stability (Conrad 1999; Stams and Plugge 2009; Meegoda *et al.* 2018).

Biological methanation intensifies this endogenous pathway by supplying controlled H_2 so that hydrogenotrophic methanogens reduce CO_2 to CH_4. The core reaction is $4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$. In power-to-gas systems, H_2 is usually produced by electrolysis using surplus renewable electricity and then coupled with biogas CO_2 (Lecker *et al.* 2017; Thema *et al.* 2019).

In-situ upgrading injects H_2 directly into the digester. It is highly integrated, but it is sensitive to H_2/CO_2 ratio, gas-liquid mass transfer, CO_2 depletion, pH increase, and interactions with the resident microbial community. Ex-situ upgrading feeds CO_2-rich biogas and H_2 into a separate methanation reactor. This allows better control of H_2 supply, mixing, retention time, and microbial enrichment, and it can be easier to couple with intermittent renewable electricity (Vanwonterghem *et al.* 2014; Agneessens *et al.* 2017; Bassani *et al.* 2017; Kougias *et al.* 2017; Xu *et al.* 2020). Bioelectrochemical upgrading is another emerging route, but its cost, complexity, and scale-up readiness remain important constraints (Ahern *et al.* 2015; Bassani *et al.* 2015; Kougias *et al.* 2017).

Sustainability and Life-cycle Perspective

BNG can be a low-carbon substitute for fossil natural gas when organic wastes are converted into useful methane and emissions from conventional waste management are avoided. AD of manure, FW, sewage sludge, agricultural residues and HCOW can displace fossil gas in heat, power, transport-fuel and grid applications. It can also reduce uncontrolled CH_4 emissions from manure storage, landfilling or open degradation, while digestate recycling can partly replace mineral fertilizers (Rehl and Müller 2011; Singlitico *et al.* 2019; Kolb *et al.* 2021).

These benefits are not automatic. Net greenhouse-gas performance depends on feedstock collection, transport, pretreatment energy, reactor operation, upgrading and compression demand, fugitive CH_4 emissions, methane slip, digestate storage, and land application. Low-carbon claims should therefore specify the functional unit, system boundary, energy mix, methane-leakage assumption, and digestate-management scenario (Ardolino *et al.* 2021; Bakkaloglu *et al.* 2022). In simplified terms, the net impact equals direct emissions from the BNG chain minus avoided emissions from alternative waste treatment and credits from fossil-gas and mineral-fertilizer substitution. The strongest mitigation cases occur when wastes are locally sourced, methane losses are minimized, low-carbon energy supplies upgrading, and digestate is safely managed (Duan *et al.* 2020; Lehtoranta *et al.* 2024).

CONCLUSIONS

Bio-natural gas (BNG) is a methane-rich upgraded gas produced through anaerobic digestion, purification, and upgrading. It can substitute for fossil natural gas in heat, power, transport-fuel and grid-injection applications. However, its climate benefit should be described as low-carbon or potentially near-carbon-neutral only under clearly defined system boundaries, because overall performance depends on methane leakage, upgrading energy, feedstock logistics, digestate management, and end-use substitution. Therefore, BNG development should be understood from a systems perspective. Feedstock selection and pretreatment influence hydrolysis efficiency and inhibitor risks. Reactor configuration and operating conditions determine anaerobic digestion (AD) stability, while the upgrading technology controls methane purity, methane loss, energy demand, and end-use compatibility. Wider deployment will require not only feedstock-specific pretreatment, robust AD operation, low-energy upgrading and effective leakage control, but also infrastructure compatibility, digestate valorization and policy frameworks that reward verified life-cycle benefits across the whole BNG value chain.

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