



JOURNAL ON COMMUNICATIONS

ISSN:1000-436X

Scopus®

REGISTERED

www.jocs.review

Engineering Evaluation and Production of Biogenic Food-grade CO_2 Capture via Biogas Treatment: A Review

[1]Darlington Eze Ekechukwu*, [1]Chima Clifford Ngumah, [1]Chinonye Chijioke, [2]Bennett Ikechukwu Eziefula and [1]Toochukwu Ekwutosi. Ogbulie.

[1]African Center of Excellence in Future Energies and Electrochemical Systems (ACE-FUELS), Federal University of Technology, Owerri, Nigeria.
[2]Oil & Gas with Energy Management, University of East London, United Kingdom.

Correspondence: Darlington Eze Ekechukwu

Abstract

It is becoming more widely accepted that carbon dioxide CO_2 is both a potential feedstock for circular carbon initiatives and climate liability. Together with interest in biogenic CO_2 recovered from biogas systems as a low-carbon substitute for CO_2 obtained from fossil fuels has increased due to the growing need for sustainable CO_2 sources in the food and health industries. With an emphasis on technological paths, purification requirements, and sustainability implications, this review offers a thorough engineering evaluation of biogenic food-grade CO_2 synthesis via biogas treatment. In addition to contaminants including hydrogen sulphide, moisture, oxygen, and trace volatile chemicals, biogas produced by anaerobic digestion of organic wastes usually contain sizable proportions of methane and biogenic CO_2. The CO_2 fraction can be extracted, refined, and upgraded to satisfy strict food-grade requirements when treated properly. However, its chemical makeup, including application-specific impurity limits, and its origin whether biogenic or fossil-based are crucial for its practical application. This review provides an insight into contemporary CO_2 capture and utilization approaches, benefits of biogenic food-grade CO_2 over fossil-based CO_2 as well as biogas as a source for biogenic CO_2 capture. It also offers an overview of engineering evaluations and production of food-grade CO_2 capture technology, it environmental and economic benefit. The major capture technologies that were considered in this review include; Chemical scrubbing (Amine scrubbing), Pressure Swing Adsorption (PSA), Membrane Separation and Cryogenic Separation. From an environmental standpoint, the review emphasizes how biogenic CO_2 capture supports circular economy models, lessens dependency on CO_2 derived from fossil fuels, and helps mitigate climate change. Future research needs, verification of biogenic origin, and regulatory implications are also included in the article. Overall, this review identifies important opportunities and obstacles for its broader adoption in sustainable food and health sector applications and offers an organized framework for comprehending the engineering, environmental, and industrial aspects of producing food-grade biogenic CO_2 via biogas treatment.

Keywords: Biogenic food-grade CO_2, Climate change, fossils-based CO_2, Biogas, CO_2 capture and utilization

1.0 Introduction

Climate change remained the most disturbing challenge of our time, mostly caused by the extraordinary increase in greenhouse gas (GHG) emissions [94]. The most important of these gases is carbon dioxide (CO_2), which is produced by the burning of fossil fuels, industrial activities, and deforestation [3]. Its buildup in the atmosphere exacerbates the greenhouse (GHG) effect, which causes extreme weather, melting ice caps, rising global temperatures, and disturbances to ecosystems and human livelihoods [33]. There is broad scientific agreement that the effects of climate change will worsen in the absence of swift action, endangering global economic stability, water supplies, and food security [104]. In addressing the root cause of global warming, CO_2 capture would help to reduce these hazards, making it exigent [51]. Carbon capture methods target current atmospheric CO_2, providing a way to undo damage already done, while renewable energy and efficiency improvements lower future emissions [61]. These strategies, which range from natural remedies like reforestation to direct air capture technologies, are crucial supplements to more comprehensive climate legislation [85]. Scaling up CO_2 capture quickly is not just necessary for the environment, but it is also morally required to protect future generations [2]. The window of opportunity for significant action is closing; thus, prompt international collaboration and innovation are essential.

According to [50], man-made CO_2 emission constitutes key influential drivers of climate change in this contemporary history. Anthropogenic activities such fossil fuel combustion, deforestation and an industrial process have been indicated to have altered the carbon cycle since the industrial revolution [29]. This can be observed through the continuous increases in GHG which consequently impact the global climate [55]. The long-lived greenhouse gas CO_2 traps heat in the atmosphere, causing average world temperatures to rise steadily. Rising sea levels, melting glaciers and polar ice sheets, and more frequent and severe heatwaves are just a few of the many effects of this warming [9,73,13]. Island suffers existential dangers, and coastal settlements are more susceptible to erosion and flooding [4]. Anthropogenic CO_2 emissions cause disruptions in atmospheric and marine systems that extend droughts, intensify storms, and change precipitation patterns in addition to raising temperatures [43]. Ocean acidification is another significant effect of increasing CO_2. Oceans absorb a large amount of CO_2 from the atmosphere, which alters the chemistry of saltwater and lowers pH levels [26]. Marine ecosystems are at risk from this process, especially coral reefs and creatures that build shells like plankton [37,20].

Millions of people depend on fisheries for food and livelihoods, and the deterioration of these systems threatens biodiversity [82]. There are significant socioeconomic and health effects of anthropogenic CO_2 emissions [92,91]. Vulnerable communities are disproportionately affected by climate-related disasters, which put a burden on governance, economy, and infrastructure [88]. Furthermore, there are increasing dangers to human well-being from indirect effects including poor air quality, food insecurity brought on by crop stress, and the expansion of diseases susceptible to climate change [44]. Figure 1 illustrates the causes of global climate change and some of its corresponding effects.



Figure 1: Causes and effects of climate change **Source:** [75].

From figure 1, it can be observed that anthropogenic activities are the primary drivers of climate which have varied and extensive impacts on temperature, biodiversity, sea level, weather pattern, land degradation, extreme weather events etc. So, reducing emissions alone is on longer sufficient, it is therefore urgent to aggressively remove CO_2 to slow and finally reverse the damage. A crucial route to reducing climate risks is provided by carbon capture technologies, which range from natural remedies like reforestation to industrial-scale direct air capture.

1.1 Overview of current CO_2 capture and utilization approaches

Current CO_2 capture and utilization (CCU) strategies concentrate on removing CO_2 from industrial sources (cement, power plants) using techniques like oxy-combustion, adsorption, membranes, and absorption (amines) [41]. The CO_2 is then either stored geologically (CCS) or transformed into useful products like fuels, chemicals, building materials, or enhanced oil recovery (EOR). Pre-combustion involving the removal of CO_2 from fossil fuels before combustion is completed, post-combustion involving the removal of CO_2 from industrial flue gases after burning fossil fuels, and Direct-air-capture Direct (DAC) which is a technology that removes CO_2 directly from ambient air using, these are all important capture techniques [98]. While high costs and storage permanence continue to be obstacles, continuous improvements in sorbents and membranes improve efficiency and cost. For the purpose of this review, it will focus on bioenergy with carbon capture through biogenic Food-grade CO_2 Capture via biogas treatment.

1.2 Biogenic CO_2 and its role in carbon cycle

As part of the natural carbon cycle, biogenic CO_2 originates from organic matter, animals, microbes and is absorbed by plants through photosynthesis. In the process, the plants disintegrate, releasing CO_2 into the atmosphere, which is then reabsorbed by other plants, forming a circular process [27]. Photosynthesis is the key driver of biogenic CO_2, plants, cyanobacteria and algae captures atmospheric CO_2 and changes it into organic matter, forming the basis of carbon storage

in biomass and food web [81]. This stored carbon subsequently gets back to the atmosphere via respiration by those microbes, and decomposition of the organic matter. These continuous cyclical web of biogenic CO_2 regulates seasonal atmospheric CO_2 concentrations [35]. Figure 2 described the biogenic and its role in carbon cycle.

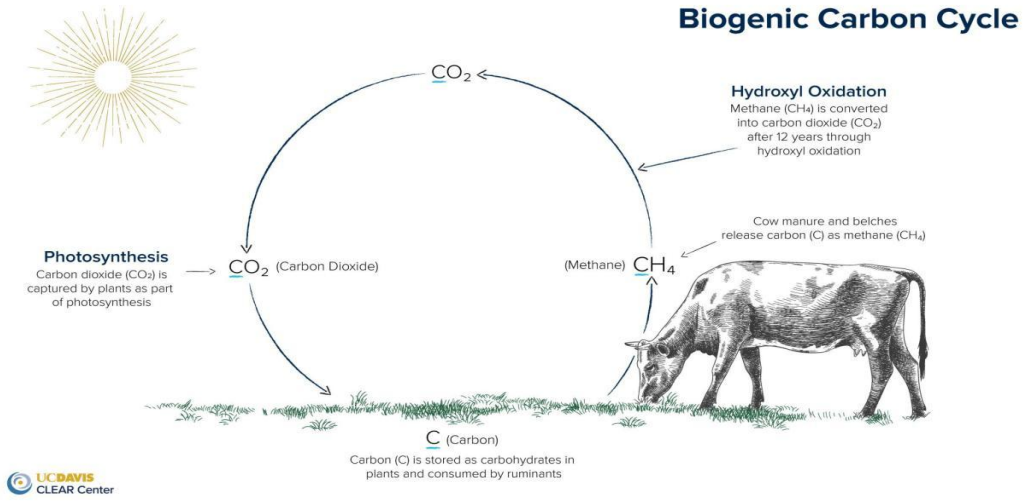


Fig. 2: Biogenic carbon web Source: [56].

Additionally, Oceans and soils are also essential parts of the biogenic carbon cycle. When organic waste is broken down by soil bacteria, some carbon in long-lived soil organic matter is stabilized and CO_2 is released [49]. Phytoplankton fixes CO_2 in marine systems, and the biological pump carries some of this carbon to deeper waters where it can be stored for decades [103]. By buffering atmospheric CO_2 levels, these activities aid in climate moderation. When emissions from burning or decaying biomass are offset by regrowth and fresh carbon absorption, biogenic CO_2 is frequently referred to as "carbon neutral [53]. However, ecological management and temporal scales determine this neutrality. Biogenic carbon sinks can become net CO_2 sources when they are disrupted by deforestation, land degradation, and ecosystem disturbance.

1.3 Advantage of biogenic CO_2 over fossils-based CO_2

As clearly stated in the above subsection, biogenic CO_2 is a component of the natural carbon cycle and is regarded as carbon neutral. Unlike the fossils-derived which add “odd” carbon into the atmosphere. The following are some key environmental advantages of biogenic CO_2

i. **Reducing reliance on fossil fuels:** Biogenic CO_2 lowers reliance on fossil fuels, which is crucial for reducing total CO_2 emissions, by encouraging the use of renewable resources and the recovery of organic waste [16].

ii. **Sustainable industrial uses:** Biogenic CO_2 can be extracted at the source, cleaned up, and used again in several different sectors. For instance, [71] suggest that CO_2 emissions from fermentation or biomass degradation can be caught and utilized for a variety of industrial uses in the wine, brewing, and methanization industries, thereby

establishing a circular economy. Biogenic CO_2 is valued in these industries, which lowers the price of buying fossil CO_2 [52].

iii. **Carbon neutral:** Unlike fossil-derived CO_2, biogenic CO_2 does not add to the overall rise in CO_2 content in the atmosphere. Because it keeps carbon emissions and absorption in balance, this trait is essential for reducing global warming [81].

1.4 Biogas as a source for biogenic CO_2 capture

Biogas is a critical component of anaerobic digestion naturally produced alongside methane; biogas is an important source for biogenic CO_2 collection [65]. This carbon source is climate neutral and is separated during biomethane upgrading. Instead of releasing this CO_2, capturing and using it increases the climate benefits of biogas and transforms it into useful feedstock for sustainable fuels (e-fuels), chemicals, food and beverage (carbonation, dry ice), and greenhouse enrichment, all of which fit into the circular economy and bio-CCUS strategies [83]. Biogenic CO_2 is produced via anerobic digestion of lignocellulose material such as (straws, food waste, or energy crops) yielding methane and CO_2 with approximately 40 – 65% and 35 – 45% respectively as its raw biogas composition [86]. Other constituents of anaerobic digestion are hydrogen sulphide, hydrogen, nitrogen, siloxanes, volatile organic compounds, oxygen and ammonia [24]. After anaerobic digestion, biogenic CO_2 can be captured, purified, and recovered right at the emission source via modern technologies. In order to maximize CO_2 utilization and build closed circular economy circuits, these technologies are critical [93]. For instance, CO_2 captured in wineries and breweries can be used to carbonate sparkling wines, inert fermenters, or shield must from oxidation [25]. These developments not only lessen reliance on fossil fuels for CO_2, but they also increase revenue for the businesses that use them [31]. This shows that it is feasible to balance financial success with environmental goals. According to [16], the biogas stream's high concentration of (25 – 50%) of CO_2 offers two opportunities: improving fuel quality and applying capture methods.

1.5 Demand for biogenic CO_2

The demand for biogenic CO_2 currently across key important industries is alarming, In Europe for instance, [12] assert that with the potential to capture enormous amounts (millions of tons) for uses in food, chemicals, and e-fuels, replacing fossil CO_2 and lowering emissions, Europe has a huge and expanding demand for biogenic CO_2, mainly from the biogas/biomethane sector. However, issues like logistics and policy frameworks must be resolved to fully unlock this significant supply for sectors like maritime shipping and aviation [100]. The demand for sustainable carbon in chemicals, e-fuels (e-methanol, e-SAF), and permanent carbon storage (BECCS) to reach net-zero targets is driving the surge in demand for biogenic CO_2; by 2050, supply and demand are expected to be drastically out of synchronize [102]. Although biogenic CO_2 is still less expensive, preferred feedstock for de-fossilization, Direct Air Capture (DAC) will be essential due to limited availability and capture issues [78]. Important industries include biogas, food/beverage

(carbonation, fermentation), and industrial processes are a few to mention areas where Biogenic CO_2 is demanded [77].

Additionally, the purity criteria and requirements for biogenic CO_2 are controlled by a few regulatory and industry-specific organizations, and they greatly depend on the intended use [48]. There is not a single, all-encompassing standard, instead, several applications (such as food, medicine, industry, and storage) have varying purity thresholds and important impurity restrictions [54]. For instance, in food and beverages, the purity requirement is above 99.9%, with impurities such as odor, moisture, and taste below 20% [60]. [76] noted that carbon monoxide, SO_2, H_2S and moisture constitute the key impurities in medicine while required purity standard is above 99.5%. To prove that requirements have been fulfilled, suppliers are frequently obliged to give a Certificate of Analysis (COA) for every batch and to have accredited quality management systems such as ISO 22000 for food safety [11].

1.6 Challenges in producing food-grade CO_2 from biogas

Although it offers a promising way to value renewable carbon streams, producing food-grade CO_2 from biogas has several technical, legal, and financial obstacles. Methane, CO_2, water vapour, hydrogen sulphide (H_2S), ammonia, siloxanes, volatile organic compounds (VOCs), and trace pollutants are commonly found in biogas, which is produced by the anaerobic digestion of organic waste. Overcoming these obstacles is necessary to transform the CO_2 percentage into food-grade quality. Key challenges in producing food-grade CO_2 form biogas stream include high contamination and complex purification. [99] identified that high-quality purification of raw biogas is essential to achieve food-grade standards, requiring over 99.9% purity. This is because biogas contain trace impurities such as hydrogen sulfide, nitrogen, oxygen, ammonia, and water vapor. Additionally, siloxanes must be removed to prevent damage to equipment, and organic residues may leave odorous compounds that are unacceptable in food-grade CO_2 [40]. The purification process is complex and multi-stage, necessitating a more rigorous approach than standard gas purification for energy production [70]. Also, high operational and capital costs in CO_2 production from biogas stem from expensive technologies like membranes and cryogenic distillation, which require significant investment and maintenance [99]. The energy-intensive nature of these processes further reduces economic viability, leading to challenges in profitability, as food-grade CO_2 production can be about 7% more costly compared to traditional fossil-based methods [69].

Feedstock variability poses challenges in biogas production due to unstable raw biogas composition, which depends on the type of feedstock used, such as waste or sewage sludge [7]. To ensure effective purification processes, a reliable and consistent high-quality feedstock is essential [47]. Additionally, logistical difficulties in the collection and transportation of organic waste hinder overall production efficiency [84,85]. Furthermore, technical and regulatory challenges in biogas processing include stringent standards for food-grade CO_2 requiring extensive testing for contaminants, methane losses up to 5% during upgrading, and high maintenance needs due to the corrosive nature of raw biogas leading to costly downtime [99,8]. Additionally, food-grade CO_2

demands liquid form, necessitating energy-intensive liquefaction and specialized pressurized storage tanks [5].

2.0 Engineering evaluation of CO_2 capture technologies from biogas

The engineering evaluation of the various CO_2 capture technologies from biogas plant is fundamentally based on cost, efficiency and technical maturity of the technology as well as its environmental effects while upgrading the capturing CO_2 constituents. The following constitute some key technologies for CO_2 capture from biogas, evaluations, their pros/cons, cost, technical maturity, environmental effects and their efficiency.

Chemical scrubbing, particularly amine scrubbing, is effective for large-scale CO_2 capture, achieving over 90% efficiency and ensuring high biomethane purity [79]. It is commercially available and well-established (TRL 9) [59]. However, it faces challenges such as high energy costs, significant solvent regeneration energy requirements, potential solvent deterioration, and equipment corrosion [105]. Environmental concerns include emissions of amines, particulates, and odors, along with risks of acidification, eutrophication, and contamination of soil and water [79]. Figure 3 showed a schematic diagram of amine scrubbing process in CO_2 post-combustion capture.

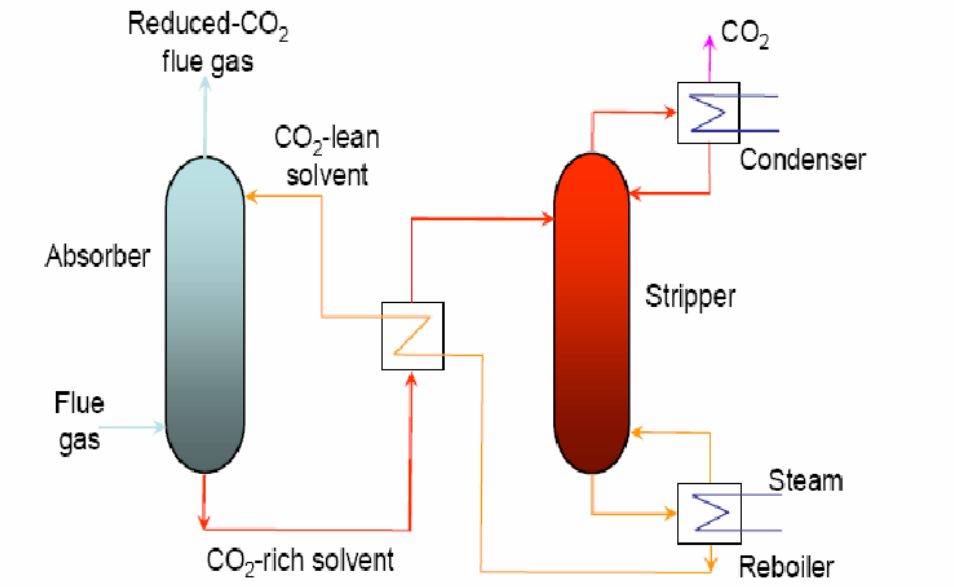


Fig. 3: Chemical scrubbing (Amine scrubbing) **Source:** [45].

Pressure Swing Adsorption (PSA) is an efficient solid technology for biogas upgrading, utilizing adsorbents like Zeolite 13X to separate CO_2 from methane during pressure cycles [66]. Engineering efforts focus on optimizing adsorbent materials and system designs to reduce methane slip, enhance energy efficiency, and accommodate variable biogas flows. PSA achieves high biomethane purity (>98%) and biogenic CO_2 purity (>99%) with low energy consumption, making it suitable for small-scale applications [1,30]. Despite its readiness for commercial use, challenges include high energy demand, limited capacity, and operational costs [1]. Ongoing research targets improvements in sorbent materials and overall system performance to further enhance separation

efficiency and recovery rates. Figure 4 illustrates the schematic diagram of Pressure Swing Adsorption (PSA).

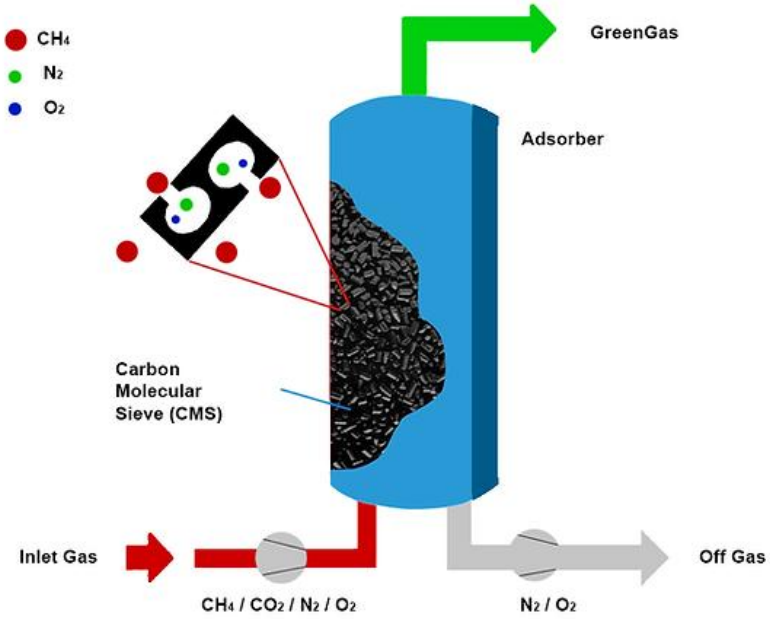


Fig. 4: Pressure Swing Adsorption (PSA) **Source:** [60].

Membrane separation technology is noted for its resistance to impurities, eco-friendliness, and compact design [28]. However, it faces limitations related to membrane material properties and recovery/purity trade-offs. Costs range from approximately $40 to over $100 per ton for biogenic capture, influenced by factors such as concentration, target purity, capture rate, and system design [89]. While innovative membranes have a Technology Readiness Level (TRL) of under 5, integrated multi-stage systems are more developed with a TRL of 7 to 9 [19]. Despite its complexity, membrane separation can achieve over 90% recovery and over 95% purity efficiency [62].

Cryogenic separation on the other hand, is a highly efficient method characterized by a purity efficiency exceeding 99%. This process is considered eco-friendly and possesses the capability to eliminate impurities at the initial stage, as indicated by [95]. Cryogenic separation is a method that entails the desublimation of solid CO_2 from a gas mixture at temperatures below 56.6 °C, enabling a physical separation process [23]. This method's primary advantage is its capacity to transform solid CO_2 into high-purity liquid CO_2, which may be effectively injected into subterranean storage systems or employed for purposes like increased oil recovery in geological formations [23]. Table 1 provides major direct air capture technologies, evaluation, advantages/disadvantages, cost, technical maturity of each technology, its environmental effects and the efficiency of the technology.

Table 1: Summary of the various direct air capture technologies

Technology	Evaluation	Advantage	Disadvantage	Cost	Technical maturity	Environmental effects	Efficiency
Chemical scrubbing (Amine scrubbing)	It is efficient for large-scale deployment where extensive level of purity is necessary [79].	It provides excellent CO_2 capture, vast operational expertise and high biomethane purity [59].	The solvent's high regeneration energy requirement, the possibility of solvent deterioration, and equipment corrosion [105].	It requires high energy cost [10]	Commercially available and highly matured (TRL 9) [87].	Major effects include amine, particulate, odour emissions. Acidification, eutrophication, soil/water contamination and ozone formation [36,72,80].	Highly effective with efficiency above 90% [64].
Pressure Swing Adsorption (PSA)	PSA is a practical, solid technology for biogas upgrading with lower energy consumption and corrosion resistance. It uses adsorbents like	Biomethane purity >98%, biogenic CO_2 >99%, Low energy use, suitable for small-scale deployment, less	Extensive energy demands for vacuum/compressors, Limited capacity [1].	High operating cost [52].	Readily available for commercial deployment but research and	High energy use, high water use, and impurities [52].	By utilising adsorbent material and pressure cycles, efficiency varies but provides high purity (90–

Zeolite 13X to separate CO_2 from methane under pressure cycles. Engineering evaluations center on optimizing adsorbent materials (e.g., Metal-Organic Frameworks) and system designs (multi-bed, multi-stage) to minimize methane slip (loss), improve energy efficiency (reducing high-cost compression), and handle variable biogas flow rates. More recently, advanced modelling, and integrated systems for both valuable CO_2 capture and high-purity	operational complexity [1], [30].	development focus on sorbent materials improvement [63].	99%) and good recovery (up to 98%) for gas separation (such as H_2, O_2, N_2, and CO_2). Key factors are adsorbent selection, multi-bed designs (for better purity/recovery balance), cycle time optimization, and managing energy costs from compression [101].

	biomethane (Mulu, M'Arimi, & Ramkat, 2021)						
Membrane Separation	Evaluation lies in its resistance to impurities and membrane material properties [28].	Eco-friendly technology, high efficiency and compact modular design [62].	Membrane material limitations concerns and recovery/purity exchanges [90].	For biogenic capture, the cost of membrane separation can vary from about $40 to more than $100 per ton of collected, other studies report particular costs of about $48/ton for industrial applications. The beginning concentration,	It is technologically matured with TRL of <5 for innovative membranes and TRL of 7 – 9 for integrated multi-stage systems [19].	Membrane material production and disposal [32].	Although it requires multistage and complex configuration, it can achieve recovery efficiency of >90% and purity efficiency of >95% [89].

		target purity and capture rate, membrane material costs, and the overall system design are some of the operating criteria that greatly influence the actual cost [74].
Cryogenic Separation	High purity efficiency of >99%, eco-friendly and has the ability to remove impurities at the initial stage [95].	

3.0 Production of biogenic food-grade CO_2: post-capture purification

According to the production of biogenic CO_2 involves the biological decomposition of organic materials such as crops residues and manure to produce biogas made up of 40% CO_2 and 60% methane. The CO_2 is often a byproduct of biomethane upgrade leading to the provision of around 99% purified biogenic CO_2. The purity of the CO_2 can further be subjected to other purification processes like cryogenic distillation to achieve about 99.9% purity [1,30]. Figure 5 depicts an illustrative diagram of process flow of biogenic CO_2 production.

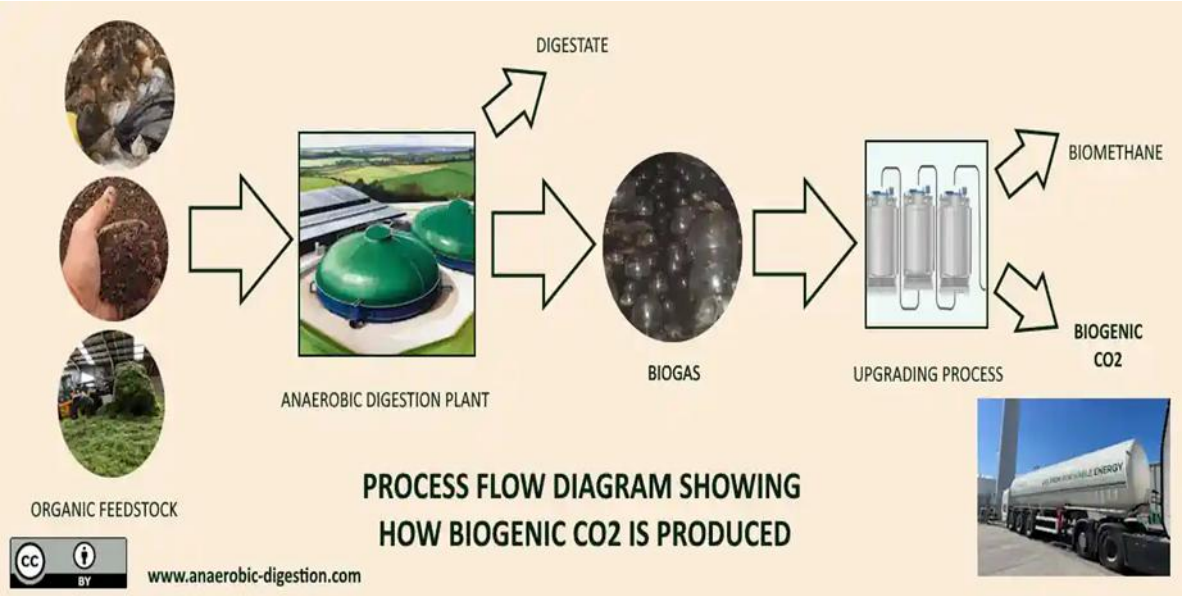


Figure 5: Process flow diagram showing the production process of biogenic CO_2

Biogenic CO_2 production from anaerobic digestion is not only a biochemical process but also one that requires evaluation through techno-economic analysis (TEA) and life cycle assessment (LCA) to determine its commercial viability and environmental performance.

3.0 Techno-Economic Analysis (TEA)

Techno-economic analysis focuses on evaluating capital investments, operational costs, and potential revenue streams in producing purified biogenic CO_2 from anaerobic digestion systems [25]. In this context, anaerobic digestion transforms agricultural residues, manure, and organic waste into biogas, which consists of about 60% methane and 40% carbon dioxide. The process of biomethane upgrading separates methane from raw biogas, producing pipeline-grade biomethane, employing technologies like pressure swing adsorption (PSA), membrane separation, water scrubbing, and chemical absorption [17]. The CO_2 recovered can reach around 99% purity, and further purification techniques, such as cryogenic distillation can increase purity to approximately 99.9% purity, and further purification techniques such as cryogenic distillation, can increase purity to approximately 99.9%, thus making it suitable for applications in beverage carbonation, chemical manufacturing, and synthetic fuel production [6].

The techno-economic perspective on the costs of biogenic CO_2 production is shaped by several key factors such as capital expenditure (CAPEX), operational expenditure (OPEX), revenue streams, and scale of operations.

Capital Expenditure (CAPEX) encompasses major costs related to anaerobic digesters, gas upgrading systems, purification units, compression equipment, and CO_2 liquefaction or storage facilities, with cryogenic systems being notably capital-intensive due to low-temperature operational demands [71, 68]. Operational Expenditure (OPEX) are operating costs that include feedstock collection, electricity for compression and separation, maintenance, labor, and chemicals for upgrading technologies. Notable, energy requirements for cryogenic processes can elevate operational expenses [68]. Revenue Steams enhance economic feasibility through diverse value streams such as the sale of biomethane as renewable natural gas, the sale of food-grade or industrial CO_2, potential carbon credits or renewable energy incentives, and the use of digestate as fertilizer. In terms of scale of operations, larger anaerobic digestion facilities typically achieve better economics of scale, while smaller operations may find it challenging to justify investments in CO_2 purification and liquefaction [71]. Recent studies indicate that the levelized cost of captured biogenic CO_2 from biogas upgrading can often be lower than that of fossil-based CO_2 capture, particularly when dealing with already concentrated CO_2 streams. However, the overall economic viability remains contingent on market demand for purified CO_2, energy prices, and existing policy incentives [67].

4.0 Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is crucial for evaluating the environmental impacts of biogenic CO_2 production, emphasizing the entire production chain from feedstock collection to CO_2 purification and utilization [97,46]. The assessment encompasses several key stages: First is the feedstock production and collection involving the collection of agriculture residues and manure, which entails energy use and emissions. Utilizing waste instead of dedicated energy crops can significantly lower environmental impacts [41]. Second is the anaerobic digestion which is the process that generates biogas while curtailing methane emissions from organic waste decomposition, thus providing substantial greenhouse gas mitigation benefits. Third is biogas upgrading and CO_2 separation, upgrading procedures require electricity and sometimes chemicals, resulting in environmental impacts that depend on the energy sources utilized. Fourth is CO_2 purification and liquefaction involving techniques such as cryogenic distillation necessitate considerable energy inputs, the carbon footprint is mitigated when renewable energy sources are employed. Lastly is utilization or storage of CO_2 when purified biogenic CO_2 can be used in carbon capture and utilization pathways, such as synthetic fuels or green chemicals, displacing fossil-derived CO_2 [18]. Permanent storage can lead to net negative emissions when integrated with bioenergy systems.

Life cycle assessments show that biogenic CO_2 capture from anaerobic digestion can significantly reduce greenhouse gas emissions, especially when methane replaces fossil natural gas and CO_2 is

utilized or stored. Environmental benefits increase with the use of waste feedstocks and renewable energy during upgrading and purification processes [22].

5.0 Integrating TEA and LCA

Combining techno-economic analysis (TEA) and life cycle assessment (LCA) yields insights into the economic feasibility and environmental sustainability of biogenic CO_2 production systems. TEA assesses cost drivers and revenue potential, while LCA evaluates climate and environmental effects. Together, they aid in technology selection, system optimization, and policy development. The production of high-purity biogenic CO_2 from anaerobic digestion is a promising approach in bioenergy and carbon management, facilitating waste valorization, renewable gas generation, and greenhouse gas reduction when conditions are optimized.

6.0 Case studies and commercial applications

There are quite a number of existing projects that presents case studies and commercial applications of biogenic CO_2. These case studies present diverse technical and commercial deployment of biogenic CO_2 capture and utilizations. Table 2 presents a summary of some key selected cases for and their regions that implement biogenic CO_2 capture and utilization.

Table 2: Selected case studies of biogenic food-grade CO_2 capture and utilization

Region	Case study firm	Feedstock	Success in CO_2 capture and commercial utilization
Europe/Germany	Bioenergy Park Güstrow	Agriculture residues, animal manure, and organic waste.	The plant successfully produces approximately 18,000 tons of food-grade liquid CO_2 annually, which is captured during biomethane upgrading and purified for use in food and beverage applications [21].
Switzerland	Nesselnbach Biogas Plant	Food waste from household and restaurants	This facility processes about 300 tons of organic waste per day. CO_2 is extracted during biomethane production, purified to food-grade quality, and sold to an industrial gas supplier for applications such as beverage carbonation and dry ice production [38].

Denmark	Nature energy (Korskro biogas plant)	Animal manure and industrial/food organic waste.	The Korskro plant implemented a multi-step CO_2 purification process to capture CO_2 from biogas production that would otherwise be emitted. The purified CO_2 is upgraded to food-grade quality for the beverage industry, supporting circular bioeconomy initiatives [96,38].
Europe/United Kingdom	HappyDrink	By-products of ethanol fermentation	The company supplies food-grade CO_2 for the catering and beverage sector, including fast-food chains. Its system ensures a reliable supply for carbonation systems, enabling continuous dispensing without frequent cylinder replacements [39].

7.0 Environmental and economic considerations

Biogenic food-grade CO_2 generation provides considerable environmental benefits by replacing fossil-based CO_2 as well as a possible new economic asset for biogas producers [42]. According to [14], the main environmental considerations in the production of food-grade CO_2 is achieving climate solutions through the capture of biogenic CO_2 from sources like biomethane/ethanol production as a substitute for fossils based industrial operations. [34] assert that biogenic food-grade CO_2 results in greenhouse gas (GHG) emissions of about 220% reduction. Biogenic food-grade CO_2 is part of the natural carbon cycle; it is carbon neutral such that no new carbon is reintroduced during its production process [12]. Additionally, Biogenic food-grade CO_2 production provides an added climate impact reduction via methane slips process, although it seems insignificant but overall provided an additional methane gas emissions reduction [57]. Although biogenic food-grade CO_2 production is designed to achieve climate change solutions, its production energy sources have to be renewable so as not to generate additional climate impact [41].

Furthermore, from economic perspectives, the production of biogenic food-grade CO_2 provided an additional revenue source which potentially enhances the economies of the producers. Although [58] noted high economic initial start-ups as the major barrier for biogenic food-grade CO_2 production. [15] emphasized that Biogenic food-grade CO_2 production lowers waste emissions, promotes circular economy objectives, and gives biogas plants a new source of income. However, it necessitates a large initial investment in collection and purification technology, and market demand, logistics, and legal requirements all affect profitability [58].

8.0 Conclusion and future outlook

The engineering evaluation and production paths for biogenic food-grade CO_2 extracted through biogas treatment have been investigated in this review, underscoring its increasing significance as a sustainable substitute for carbon dioxide obtained from fossil fuels. Biogas systems present a special chance to recover high-purity, biogenic CO_2 and generate renewable energy at the same time, especially when combined with anaerobic digestion and upgrading technology. Technological developments in gas separation, purification, and polishing have shown that, with the right technical controls, monitoring, and quality assurance frameworks in place, CO_2 recovered from biogas may satisfy strict food-grade requirements. As previously said, this strategy contributes to climate change mitigation through averted emissions and upholds the ideals of the circular economy by valuing carbon streams obtained from garbage.

Despite its potential, a number of obstacles still exist. These include the necessity for uniform regulatory standards for biogenic food-grade CO_2, energy needs for purification and liquefaction, scale-dependent economic viability, and biogas composition unpredictability. For small and medium-sized systems in particular, reliable safety procedures and efficient, low-energy purification solutions are necessary to guarantee constant adherence to food and health industry regulations. For broader deployment and commercialization, these obstacles must be removed. In order to improve efficiency and dependability, integrated system design which combines biogas upgrading, CO_2 capture, renewable energy inputs, and digital monitoring is the key to the future of biogenic food-grade CO_2. Advanced membranes, solid sorbents, and modular capture units are examples of emerging technologies that are anticipated to lower costs and increase scalability, even at decentralized and community-level facilities. Additionally, market adoption is expected to be accelerated by the growing demand for sustainable CO_2 in the food, beverage, medical, and agricultural sectors, which is supported by carbon accounting systems and certification programs that acknowledge biogenic origin. In conclusion, biogenic food-grade CO_2 captured by biogas treatment is an environmentally advantageous and technically feasible approach. Its full potential as a low-carbon solution within future sustainable industrial systems will depend on ongoing research, encouraging legislative frameworks, and industry cooperation.

9.0 References

1. Abd, A. A., Othman, M. R., Helwani, Z., & Kim, J. (2024). An overview of biogas upgrading via pressure swing adsorption: Navigating through bibliometric insights towards a conceptual framework and future research pathways. *Energy conversion and management*, *306*, 118268. https://doi.org/10.1016/j.enconman.2024.118268.
2. Alalaiwat, D., & Khan, E. (2023). Current status and future scenarios of carbon capture from power plants emission: a review. *Reviews in Environmental Science and Bio/Technology*, *22*(3), 799-822. https://doi.org/10.1007/s11157-023-09663-2.
3. Andrew, R. M. (2020). A comparison of estimates of global carbon dioxide emissions from fossil carbon sources. *Earth System Science Data*, *12*(2), 1437-1465. https://doi.org/10.5194/essd-12-1437-2020.

4. Arnell, N. W., Lowe, J. A., Challinor, A. J., & Osborn, T. J. (2019). Global and regional impacts of climate change at different levels of global temperature increase. *Climatic Change*, *155*(3), 377-391. https://doi.org/10.1007/s10584-019-02464-z.
5. Aiml. (2018). *How Is Food Grade CO2 Mass Produced? – AIML Group*. Aiml.com.ng. https://aiml.com.ng/how-is-food-grade-co2-mass-produced/
6. Arrhenius, K., Hultmark, S., de Krom, I., Meijer, L., Henderson, E., & van Wijk, J. (2025). Quality of biogenic carbon dioxide stream from biogas plants including analytical method development. *Journal of CO2 Utilization*, *92*, 103020. https://doi.org/10.1016/j.jcou.2025.103020
7. Bidiko, G. B., Sangib, E. B., & Gnaro, M. A. (2025). Optimization of biogas production through co-digestion of cafeteria food waste and cow dung using the response surface methodology. *Frontiers in Energy Research*, *13*. https://doi.org/10.3389/fenrg.2025.1568478
8. Brugger, C. (2024). *Biogas — Challenges and Potentials I PowerUP*. PowerUp – Parts for Gas-Engines. https://www.powerup.at/knowledge/biogas/challenges-potentials-biogas/
9. Barange, M., Bahri, T., Beveridge, M. C., Cochrane, K. L., Funge-Smith, S., & Poulain, F. (2018). Impacts of climate change on fisheries and aquaculture. *United Nations' Food and Agriculture Organization*, *12*(4), 628-635. https://www.researchgate.net/profile/Manuel-Barange/publication/325871167_Impacts_of_Climate_Change_on_Fisheries_and_Aquaculture_
10. Bertone, M., Stabile, L., Cortellessa, G., Arpino, F., & Buonanno, G. (2024). Techno-Economic Assessment of Amine-Based Carbon Capture in Waste-to-Energy Incineration Plant Retrofit. *Sustainability*, *16*(19), 8468. https://doi.org/10.3390/su16198468.
11. Chen, H., Liu, S., Chen, Y., Chen, C., Yang, H., & Chen, Y. (2020). Food safety management systems based on ISO 22000: 2018 methodology of hazard analysis compared to ISO 22000: 2005. *Accreditation and Quality Assurance*, *25*(1), 23-37. https://doi.org/10.1007/s00769-019-01409-4.
12. Christianides, D., Bagaki, D.A., Timmers, R.A., Zrimec, M.B., Theodoropoulou, A., Angelidaki, I., Kougias, P., Zampieri, G., Kamergi, N., Napoli, A. and Malamis, D. (2025). Biogenic CO2 Emissions in the EU Biofuel and Bioenergy Sector: Mapping Sources, Regional Trends, and Pathways for Capture and Utilisation. *Energies*, *18*(6), p.1345. https://doi.org/10.3390/en18061345.
13. Clarke, B., Otto, F., Stuart-Smith, R., & Harrington, L. (2022). Extreme weather impacts of climate change: an attribution perspective. *Environmental Research: Climate*, *1*(1), 012001. **DOI** 10.1088/2752-5295/ac6e7d.
14. Cordova, S. S., Moestedt, J., Rasmussen, J., Edholm, G., Olsson, G., Nordell, E., & Gustafsson, M. (2026). What is the climate and economic impact of incorporating food-grade CO_2 production in biomethane production plants? A Swedish case study. *Energy Reports*, *15*, 108903. https://doi.org/10.1016/j.egyr.2025.12.040.
15. Cordova, S. S., Rasmussen, J., & Gustafsson, M. (2025). Barriers and drivers for biogenic CO_2 utilization: implications for the future market. *Sustainable Production and Consumption*, *56*, 490-503. https://doi.org/10.1016/j.spc.2025.04.007.
16. Czekała, W. (2022). Biogas as a sustainable and renewable energy source. In *Clean fuels for mobility* (pp. 201-214). Singapore: Springer Singapore. https://doi.org/10.1007/978-981-16-8747-1_10.

17. Cristina. (2025). *Capturing biogenic CO_2*. Novomof.com. https://blog.novomof.com/capturing-biogenic-co2
18. Disaro, A., Felici, P., Orsetti, A., & Ferrari, F. (2025). On the Path to Efficient CO_2 Liquefaction: Overcoming Limits for Large-scale CCS Projects. *Chemical Engineering Transactions*, *119*, 145–150. https://doi.org/10.3303/CET25119025
19. Dai, Z., & Deng, L. (2024). Membranes for CO_2 capture and separation: Progress in research and development for industrial applications. *Separation and Purification Technology*, *335*, 126022. https://doi.org/10.1016/j.seppur.2023.126022.
20. Doney, S. C., Busch, D. S., Cooley, S. R., & Kroeker, K. J. (2020). The impacts of ocean acidification on marine ecosystems and reliant human communities. *Annual Review of Environment and Resources*, *45*(1), 83-112. https://doi.org/10.1146/annurev-environ-012320-083019.
21. EnviTec Biogas AG. (2023). *Biomethane plant including bio-LNG in Güstrow | EnviTec Biogas*. Envitec-Biogas.com. https://www.envitec-biogas.com/references/guestrow?
22. FAO. (2024, April 30). *Biogenic CO2 use and storage to enhance the circularity and climate benefits of biogas*. GBEP; FAO. https://www.fao.org/in-action/global-bioenergy-partnership/news-and-events/news/news-detail/biogenic-co2-use-and-storage-to-enhance-the-circularity-and-climate-benefits-of-biogas/en
23. Fu, L., Ren, Z., Si, W., Ma, Q., Huang, W., Liao, K., Huang, Z., Wang, Y., Li, J., & Xu, P. (2022). Research progress on CO2 capture and utilization technology. *Journal of CO2 Utilization*, *66*, 102260. https://doi.org/10.1016/j.jcou.2022.102260
24. Fermoso, F. G., Serrano, A., Alonso-Fariñas, B., Fernández-Bolaños, J., Borja, R., & Rodríguez-Gutiérrez, G. (2018). Valuable compound extraction, anaerobic digestion, and composting: a leading biorefinery approach for agricultural wastes. *Journal of Agricultural and Food Chemistry*, *66*(32), 8451-8468. https://pubs.acs.org/doi/10.1021/acs.jafc.8b02667.
25. Fetrat, S. (2024). Biogas Production from Organic Materials. *Journal of Electrical Systems*, 20(3), 4428-4435 https://doi.org/10.52783/jes.5771.
26. Findlay, H. S., & Turley, C. (2021). Ocean acidification and climate change. In *Climate change* (pp. 251-279). Elsevier. https://doi.org/10.1016/B978-0-12-821575-3.00013-X.
27. Füchsl, S., Huber, J., Fröhling, M., & Röder, H. (2025). Balancing the green carbon cycle Biogenic carbon within life cycle assessment. *The International Journal of Life Cycle Assessment*, 1-14. https://doi.org/10.1007/s11367-025-02469-0.
28. Gabrielli, P., Gazzani, M., & Mazzotti, M. (2017). On the optimal design of membrane-based gas separation processes. *Journal of Membrane Science*, *526*, 118-130. https://doi.org/10.1016/j.memsci.2016.11.022.
29. Gakaev, R., & Daukaev, A. (2024). Natural and man-made climate changes in the holocene. *Reliability: Theory & Applications*, *19*(SI 6 (81), 637-641. DOI: 10.24412/1932-2321-2024-681-637-641.
30. Ganesan, S., Canevesi, R. L., & Grande, C. A. (2025). Simplified and cost-effective pressure swing adsorption system for simultaneous production of bio-methane & biogenic CO2 from biogas. *Energy Conversion and Management*, *325*, 119398. https://doi.org/10.1016/j.enconman.2024.119398.
31. Gebreegziabher, B. W., Dubale, A. A., Adaramola, M. S., & Morken, J. (2025). Advancing anaerobic digestion of biodiesel byproducts: A comprehensive review. *BioEnergy Research*, *18*(1), 15. https://doi.org/10.1007/s12155-025-10820-4.

32. Gkotsis, P., Peleka, E., & Zouboulis, A. (2023). Membrane-based technologies for post-combustion CO2 capture from flue gases: Recent progress in commonly employed membrane materials. *Membranes*, *13*(12), 898. https://doi.org/10.3390/membranes13120898.
33. Gür, T. M. (2022). Carbon dioxide emissions, capture, storage and utilization: Review of materials, processes and technologies. *Progress in Energy and Combustion Science*, *89*, 100965. https://doi.org/10.1016/j.pecs.2021.100965.
34. Gustafsson, M., Meneghetti, R., Souza Marques, F., Trim, H., Dong, R., Al Saedi, T., Rasi, S., Thual, J., Kornatz, P., Wall, D. and Berntsen, C. (2024). A perspective on the state of the biogas industry from selected member countries. In *IEA Bioenergy Task* (Vol. 37, No. 2024, p. 2). https://task37.ieabioenergy.com/wp-content/uploads/sites/32/2024/10/IEA_Bioenergy_T37_CountryReportSummary_2024.pdf.
35. Hansson, J., Hackl, R., Taljegard, M., Brynolf, S., & Grahn, M. (2017). The potential for electrofuels production in Sweden utilizing fossil and biogenic CO2 point sources. *Frontiers in Energy Research*, *5*, 4. https://doi.org/10.3389/fenrg.2017.00004.
36. Heo, J., McCoy, S. T., & Adams, P. J. (2017). Implications of ammonia emissions from post-combustion carbon capture for airborne particulate matter. *Environmental science & technology*, *49*(8), 5142-5150. https://pubs.acs.org/doi/10.1021/acs.est.5b00550.
37. Hoegh-Guldberg, O., Poloczanska, E. S., Skirving, W., & Dove, S. (2017). Coral reef ecosystems under climate change and ocean acidification. *Frontiers in marine science*, *4*, 252954. https://doi.org/10.3389/fmars.2017.00158.
38. International Energy Agency Bioenergy (2024). Renewable CO2 from food waste-based biogas – a case story from Switzerland. Avilable at: https://www.ieabioenergy.com/blog/publications/renewable-co2-from-food-waste-based-biogas-a-case-story-from-switzerland/.
39. HappyDrink Ltd. (2020). *Happydrink | SIAD*. Siad.com. https://www.siad.com/products/gases-for-food-use/happydrink
40. IEA. (2024). *New Publication – Case story: Production of food grade sustainable CO2 from a large biogas facility (Denmark) | Bioenergy*. Ieabioenergy.com. https://www.ieabioenergy.com/blog/publications/new-publication-case-story-production-of-food-grade-sustainable-co2-from-a-large-biogas-facility-denmark/
41. IEA Bioenergy. (2020). *Production of food grade sustainable CO 2 from a large biogas facility GO'CO2 at The Korskro Biogas Plant, Denmark. Case Story*. https://www.ieabioenergy.com/wp-content/uploads/2020/11/Case-Story-CO2-recovery-Denmark-November-2020.pdf
42. IEA Bioenergy. (2024). *Case studies of CO2 utilization in the production of ethanol – Bioenergy*. Ieabioenergy.com. https://www.ieabioenergy.com/blog/publications/case-studies-of-co2-utilization-in-the-production-of-ethanol/
43. Jha, M. K., & Dev, M. (2024). Impacts of climate change. In *Smart internet of things for environment and healthcare* (pp. 139-159). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-70102-3_10.
44. John, S. (2025). The Unequal Burden: Climate Change and Vulnerable Populations. In *Gender, Environment, and Human Rights: An Intersectional Exploration* (pp. 359-380). IGI Global. DOI: 10.4018/979-8-3693-6069-9.ch01.

45. Jabraeelzadeh, A., Gharehghani, A., Saray, J. A., Andwari, A. M., & Borhani, T. N. (2024). Techno-economic analysis of biogas upgrading through amine scrubbing: A comparative study of different single amines. *Fuel*, *381*, 133662–133662. https://doi.org/10.1016/j.fuel.2024.133662
46. Kalkan, S. T. (2020, October 7). *Life Cycle Assessment for Biogas/Biomethane Production*. ResearchGate; unknown. https://www.researchgate.net/publication/348383505_Life_Cycle_Assessment_for_BiogasBiomethane_Production
47. Kamble, A. D., Vinod, K. S., Chavan , P. D., & Vinod, A. M. (2019). Co-gasification of coal and biomass an emerging clean energy technology: Status and prospects of development in Indian context. *International Journal of Mining Science and Technology*, *29*(2), 171–186. https://doi.org/10.1016/j.ijmst.2018.03.011
48. Kajolinna, T., Balshakou, S., & Mustonen, J. (2025). Assessment of carbon dioxide quality from industrial point sources for carbon utilization. *International Journal of Greenhouse Gas Control*, *148*, 104527. https://doi.org/10.1016/j.ijggc.2025.104527.
49. Kavya, S. R., Rani, B., Banu, M. R., & Jabin, P. P. (2023). Carbon sequestration and stabilisation mechanisms in the agricultural soils: A review. *Int. J. Plant Soil Sci*, *35*(13), 79-94. https://www.sdiarticle5.com/review-history/99738.
50. Khairullina, E. R., Bogdanova, V. I., Slepneva, E. V., Nizamutdinova, G. F., Fatkhullina, L. R., Kovalenko, Y. A., & Skutelnik, O. A. (2019). Global climate change: Cyclical nature of natural and permanent nature of man-made processes. *EurAsian Journal of BioSciences*, *13*(2), 2311-2316. https://www.proquest.com/scholarly-journals/global-climate-change-cyclical-nature-natural/docview/2339039833/se-2.
51. Khan, M. K., Khan, M. I., & Rehan, M. (2020). The relationship between energy consumption, economic growth and carbon dioxide emissions in Pakistan. *Financial innovation*, *6*(1), 1. https://doi.org/10.1186/s40854-019-0162-0.
52. Kohlheb, N., Wluka, M., Bezama, A., Thrän, D., Aurich, A., & Müller, R. A. (2021). Environmental-economic assessment of the pressure swing adsorption biogas upgrading technology. *BioEnergy Research*, *14*(3), 901-909. https://doi.org/10.1007/s12155-020-10205-9.
53. Le Moigne, F. A. (2019). Pathways of organic carbon downward transport by the oceanic biological carbon pump. *Frontiers in Marine Science*, *6*, 634.
54. Leuter, P., Fendt, S., & Spliethoff, H. (2024). Requirements on synthesis gas from gasification for material and energy utilization: a mini review. *Frontiers in Energy Research*, *12*, 1382377. https://doi.org/10.3389/fenrg.2024.1382377.
55. Li, Y., Zheng, Z., Qin, Y., & Rong, P. (2021). Relative contributions of natural and man-made factors to vegetation cover change of environmentally sensitive and vulnerable areas of China. *Journal of Cleaner Production*, *321*, 128917. https://doi.org/10.1016/j.jclepro.2021.128917.
56. Liu, T. C., Wu, Y. C., & Chau, C. F. (2023). An overview of carbon emission mitigation in the food industry: efforts, challenges, and opportunities. *Processes*, *11*(7), 1993. https://www.mdpi.com/2227-9717/11/7/1993#.
57. Liu, W., Yu, Z., Xie, X., Von Gadow, K., & Peng, C. (2018). A critical analysis of the carbon neutrality assumption in life cycle assessment of forest bioenergy systems. *Environmental Reviews*, *26*(1), 93-101.

58. Liu, W., Zhu, Q., Zhou, X., & Peng, C. (2019). Comparative analyses of different biogenic CO2 emission accounting systems in life cycle assessment. *Science of the total environment*, *652*, 1456-1462.https://doi.org/10.1016/j.scitotenv.2018.11.039.
59. Loachamin, D., Casierra, J., Calva, V., Palma-Cando, A., Ávila, E. E., & Ricaurte, M. (2024). Amine-based solvents and additives to improve the CO2 capture processes: a review. *ChemEngineering*, *8*(6), 129. https://doi.org/10.3390/chemengineering8060129.
60. Lorena, L. F. R. (2024). A2. 2.1: Current Documentary Standards or Technical Specifications for Quality Assurance Hydrogen (for Heat), Biomethane and Carbon Dioxide for CCUS. https://www.decarbgrid.eu/app/uploads/sites/19/2022/04/Report-A2.2.1-Standards-or-technical-specifications-for-QA-hydrogen-for-heat-biomethane-and-carbon-dioxide-for-CCS.pdf.
61. Madejski, P., Chmiel, K., Subramanian, N., & Kuś, T. (2022). Methods and techniques for CO2 capture: Review of potential solutions and applications in modern energy technologies. *Energies*, *15*(3), 887. https://doi.org/10.3390/en15030887.
62. Mahenthiran, A. V., & Jawad, Z. A. (2021). A prospective concept on the fabrication of blend pes/peg/dmf/nmp mixed matrix membranes with functionalised carbon nanotubes for co2/n2 separation. *Membranes*, *11*(7), 519. https://www.mdpi.com/2077-0375/11/7/519#.
63. Medrano, J. A., Llosa-Tanco, M. A., Tanaka, D. A. P., & Gallucci, F. (2019). Membranes utilization for biogas upgrading to synthetic natural gas. In *Substitute Natural Gas from Waste* (pp. 245-274). Academic Press. https://doi.org/10.1016/B978-0-12-815554-7.00010-6.
64. Meng, F., Ju, T., Han, S., Lin, L., Li, J., Chen, K., & Jiang, J. (2023). Novel low energy mixed amine biphasic solvent for carbon dioxide capture in biogas upgrading. *Separation and Purification Technology*, *326*, 124724. https://doi.org/10.1016/j.seppur.2023.124724.
65. Modestra, J. A., Katakojwala, R., & Mohan, S. V. (2020). CO2 fermentation to short chain fatty acids using selectively enriched chemolithoautotrophic acetogenic bacteria. *Chemical Engineering Journal*, *394*, 124759. https://doi.org/10.1016/j.cej.2020.124759.
66. Mulu, E., M'Arimi, M. M., & Ramkat, R. C. (2021). A review of recent developments in application of low-cost natural materials in purification and upgrade of biogas. *Renewable and Sustainable Energy Reviews*, *145*, 111081. https://doi.org/10.1016/j.rser.2021.111081.
67. Maes, Y. (2025, August 12). *Biogenic CO2 vs Fossil CO2*. Solveno Technologies | Biogenic CO2 vs Fossil CO2; Solveno Technologies. https://www.solvenotechnologies.com/en/news/biogenic-co2-vs-fossil-co2
68. Mapantsela, Y., & Mukumba, P. (2025). Biogas Upgrading and Bottling Technologies: A Critical Review. *Energies*, *18*(24), 6506. https://doi.org/10.3390/en18246506
69. Marchiori, P., Ferreira, V. C., Luana, Castro, E. N., Sillero, L., Zanin, H. G., & Tânia Forster-Carneiro. (2025). Global trends and challenges in biogas purification and CO $_2$ capture for renewable energy and climate mitigation. *Biofuels Bioproducts and Biorefining*, *19*(6), 2474–2494. https://doi.org/10.1002/bbb.2805
70. Mehta, N. K., Sharma, S., Triphati, H. H., Satvik, K., K. Aruna, Choudhary, B. K., & Meena, D. K. (2023). Conversion of fish processing waste to value-added commodities: a waste to wealth strategies for greening of the environment. *Elsevier EBooks*, 421–466. https://doi.org/10.1016/b978-0-323-99145-2.00005-7
71. Nouwe Edou, D. J., & Onwudili, J. A. (2022). Comparative techno-economic modelling of large-scale thermochemical biohydrogen production technologies to fuel public buses: A

case study of West Midlands region of England. *Renewable Energy*, *189*, 704–716. https://doi.org/10.1016/j.renene.2022.02.074

72. Neerup, R., Rasmussen, V.E., Vinjarapu, S.H., Larsen, A.H., Shi, M., Andersen, C., Fuglsang, K., Gram, L.K., Nedenskov, J., Kappel, J. and Blinksbjerg, P. (2023). Solvent degradation and emissions from a CO2 capture pilot at a waste-to-energy plant. *Journal of Environmental Chemical Engineering*, *11*(6), p.111411. https://doi.org/10.1016/j.jece.2023.111411.
73. Nunez, S., Arets, E., Alkemade, R., Verwer, C., & Leemans, R. (2019). Assessing the impacts of climate change on biodiversity: is below 2°C enough? *Climatic Change*, *154*(3), 351-365. https://doi.org/10.1007/s10584-019-02420-x.
74. Park, J. W., Heo, S., Yeo, J. G., Lee, S., Kim, J. K., & Lee, J. H. (2025). Membrane-Based CO2 Capture Across Industrial Sectors: Process Conditions, Case Studies, and Implementation Insights. *Membranes*, *15*(7), 200. https://doi.org/10.3390/membranes15070200.
75. Pechsiri, J. (2010). A Review of the Climate-Change-Impacts' Rates of Change in the Arctic. Journal of Environmental Protection 01(1), 59-69. https://doi.org/10.4236/jep.2010.11008.
76. Pscherer, T., & Krommes, S. (2025). LCA standards for environmental product assessments in the bioeconomy with a focus on biogenic carbon: A systematic review. *The International Journal of Life Cycle Assessment*, *30*(2), 371-393. ttps://doi.org/10.1007/s11367-024-02387-7.
77. Rachman, G. A., & Nur, S. M. (2025). Bioenergy Industry Management Challenges and Opportunities in the Energy Transition Era. *Journal of mechanical engineering manufactures materials and energy*, *9*(1), 153-167. https://doi.org/10.31289/jmemme.v9i1.14015.
78. Reid, W. V., Ali, M. K., & Field, C. B. (2020). The future of bioenergy. *Global change biology*, *26*(1), 274-286. https://doi.org/10.1111/gcb.14883.
79. Rochelle, G. T. (2019). Amine scrubbing for CO2 capture. *Science*, *325*(5948), 1652-1654. https://doi.org/10.1126/science.1176731.
80. Rochelle, G. T. (2024). Air pollution impacts of amine scrubbing for CO2 capture. *Carbon Capture Science & Technology*, *11*, 100192. https://doi.org/10.1016/j.ccst.2024.100192.
81. Rozhnov, S. V., Lukina, N. V., & Alekseev, A. O. (2024). Biogenic and Abiogenic Carbon Cycles in Time and Space and the Scale of the Impact of Anthropogenic Factors on Them: Introduction. https://doi.org/10.1134/S1062359024613314.
82. Sahoo, G., Mishra, P., Wani, A.M., Sharma, A., Mishra, D., Patra, D., Mishra, I. and Behera, M. (2023). Impact of climate change on livelihood security and biodiversity–issues and mitigation strategies. In *Climate Change Impacts on Natural Resources, Ecosystems and Agricultural Systems* (pp. 1-27). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-19059-9_1.
83. Sahota, S., Lombardi, L., Singh, D., O'Donoghue, C., Geoghegan, C., Rova, U., Christakopoulos, P., Matsakas, L. and Sarkar, O., 2026. CO2 from biogas: valorisation, economic and environmental impacts in circular carbon systems. *Reviews in Environmental Science and Bio/Technology*, *25*(1), p.6. https://doi.org/10.1007/s11157-025-09755-1.

84. Saboohi, Z., & Hosseini, S. E. (2024). Advancements in Biogas Production: Process Optimization and Innovative Plant Operations. *Clean Energy*. https://doi.org/10.1093/ce/zkae096
85. Saxena, A., Prakash Gupta, J., Tiwary, J.K., Kumar, A., Sharma, S., Pandey, G., Biswas, S. and Raghav Chaturvedi, K. (2024). Innovative pathways in carbon capture: Advancements and strategic approaches for effective carbon capture, utilization, and storage. *Sustainability*, *16*(22), p.10132. https://www.mdpi.com/2071-1050/16/22/10132#.
86. Sen, R., & Mukherjee, S. (2024). Recent advances in microalgal carbon capture and utilization (bio-CCU) process vis-à-vis conventional carbon capture and storage (CCS) technologies. *Critical Reviews in Environmental Science and Technology*, *54*(24), 1777-1802. https://doi.org/10.1080/10643389.2024.2361938.
87. Sieborg, M. U., Nielsen, A. K. H., Ottosen, L. D. M., Daasbjerg, K., & Kofoed, M. V. W. (2024). Bio-integrated carbon capture and utilization: at the interface between capture chemistry and archaeal CO2 reduction. *Nature Communications*, *15*(1), 7492. https://doi.org/10.1038/s41467-024-51700-3.
88. Smith, G. S., Anjum, E., Francis, C., Deanes, L., & Acey, C. (2022). Climate change, environmental disasters, and health inequities: the underlying role of structural inequalities. *Current environmental health reports*, *9*(1), 80-89. https://doi.org/10.1007/s40572-022-00336-w.
89. Song, C., Run, L., Liu, Q., Deng, S., Li, H., & Sun, J. (2024). Membrane-cryogenic hybrid CO2 capture—A review. *Carbon Capture Science & Technology*, *13*, 100249. https://doi.org/10.1016/j.ccst.2024.100249.
90. Sreenath, S., & Sam, A. A. (2023). Hybrid membrane-cryogenic CO2 capture technologies: A mini-review. *Frontiers in Energy Research*, *11*, 1167024. https://doi.org/10.3389/fenrg.2023.1167024.
91. Tang, L., Furushima, Y., Honda, Y., Hasegawa, T., & Itsubo, N. (2019). Estimating human health damage factors related to CO2 emissions by considering updated climate-related relative risks. *The International Journal of Life Cycle Assessment*, *24*(6), 1118-1128. https://doi.org/10.1007/s11367-018-1561-6.
92. Tang, L., Ii, R., Tokimatsu, K., & Itsubo, N. (2018). Development of human health damage factors related to CO2 emissions by considering future socioeconomic scenarios. *The International Journal of Life Cycle Assessment*, *23*(12), 2288-2299. https://doi.org/10.1007/s11367-015-0965-9.
93. Theodoropoulou, A., Bagaki, D.A., Gaspari, M., Kougias, P., Treu, L., Campanaro, S., Hidalgo, D., Timmers, R.A., Zrimec, M.B., Reinhardt, R. and Grimalt-Alemany, A. (2025). Technological Approaches for the Capture and Reuse of Biogenic Carbon Dioxide Towards Sustainable Anaerobic Digestion. *Sustainability*, *17*(22), p.10385. https://www.mdpi.com/2071-1050/17/22/10385#.
94. Ugah, E. T. A., Ndubuisi, O. G., Ali, E. P. S. E., Obiorah, C. A., Nesiama, O., Agbakhamen, E. C. O., & Okoro, E. O. P. (2025). Global climate change: carbon capture technologies and their roles in the mitigation of climate change. *IPHO-Journal of Advance Research in Science and Engineering*, *3*(02), 22-35. https://iphopen.org/index.php/se/article/view/270.
95. Upadhyay, A., Kovalev, A.A., Zhuravleva, E.A., Kovalev, D.A., Litti, Y.V., Masakapalli, S.K., Pareek, N. and Vivekanand, V. (2022). Recent development in physical, chemical,

biological and hybrid biogas upgradation techniques. *Sustainability*, *15*(1), p.476. https://doi.org/10.3390/su15010476.

96. Uabio. (2021). *Korskro biogas plant (Denmark) – element of the circular economy*. Uabio.org. https://uabio.org/en/news/11446/
97. Wang, X., Wang, J., Duan, C., Wang, X., & Liang, D. (2025). Systematic Review on the Life Cycle Assessment of Manure-Based Anaerobic Digestion System. *Sustainability*, *17*(19), 8926–8926. https://doi.org/10.3390/su17198926
98. Wang, Y., Mu, X., Hu, G., Wang, L., & Zhu, X. (2025). Life Cycle Assessment-Based Analysis of Environmental and Economic Benefits in Construction Solid Waste Recycling. *Sustainability*, *17*(9), 3872–3872. https://doi.org/10.3390/su17093872
99. Werkneh, A. A. (2022). Biogas impurities: environmental and health implications, removal technologies and future perspectives. *Heliyon*, *8*(10), e10929. https://doi.org/10.1016/j.heliyon.2022.e10929
100. Wu, F., & Pfenninger, S. (2023). Challenges and opportunities for bioenergy in Europe: National deployment, policy support, and possible future roles. *Bioresource Technology Reports*, *22*, 101430. https://doi.org/10.1016/j.biteb.2023.101430.
101. Yang, Q., Chai, J., Yang, L., Chen, Z., Qin, Y., Wang, T., Sun, W. and Wang, C. (2025). Optimization and comparison of multi-beds PSA technology for separation of carbon dioxide mixtures by processes simulations. *Cleaner Chemical Engineering*, p.100180. https://doi.org/10.1016/j.clce.2025.100180.
102. Zabaniotou, A. (2018). Redesigning a bioenergy sector in EU in the transition to circular waste-based Bioeconomy-A multidisciplinary review. *Journal of Cleaner Production*, *177*, 197-206. https://doi.org/10.1016/j.jclepro.2017.12.172.
103. Zafrilla, B., Matarredona, L., Bonete, M. J., Zafrilla, G., & Esclapez, J. (2024). Phytoplankton as CO2 sinks: Redirecting the carbon cycle. *Applied Sciences*, *14*(19), 8657. https://doi.org/10.3390/app14198657.
104. Zhang, S., Shen, Y., Zheng, C., Xu, Q., Sun, Y., Huang, M., Li, L., Yang, X., Zhou, H., Ma, H. and Li, Z. (2024). Recent advances, challenges, and perspectives on carbon capture. *Frontiers of Environmental Science & Engineering*, *18*(6), p.75. https://doi.org/10.1007/s11783-024-1835-0.
105. Zhao, F., Cui, C., Dong, S., Xu, X., & Liu, H. (2023). An overview on the corrosion mechanisms and inhibition techniques for amine-based post-combustion carbon capture process. *Separation and Purification Technology*, *304*, 122091. https://doi.org/10.1016/j.seppur.2022.122091.

List of figures



Figure 1: Causes and effects of climate change **Source:** [75].

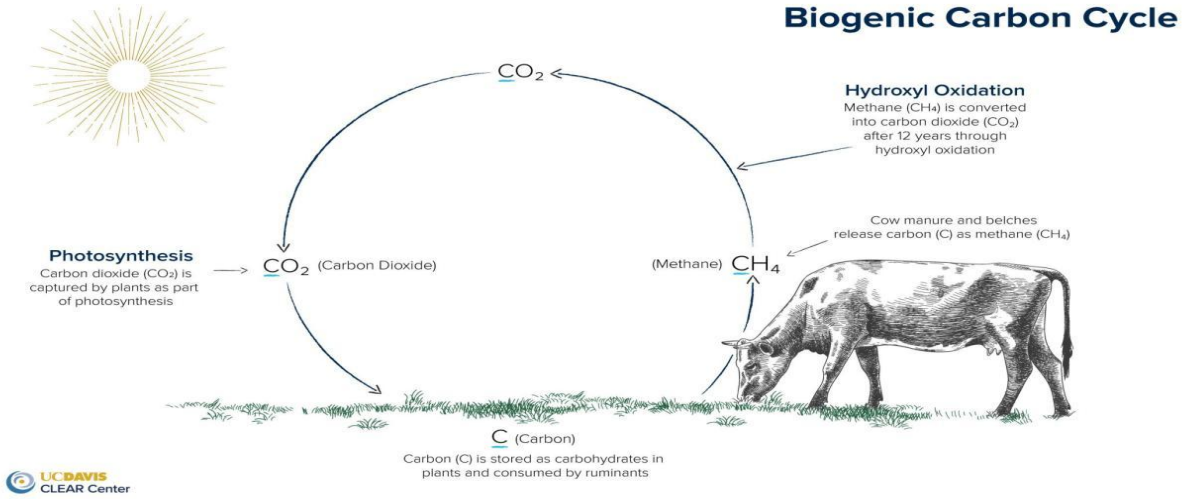


Fig. 2: Biogenic carbon web Source: [56].

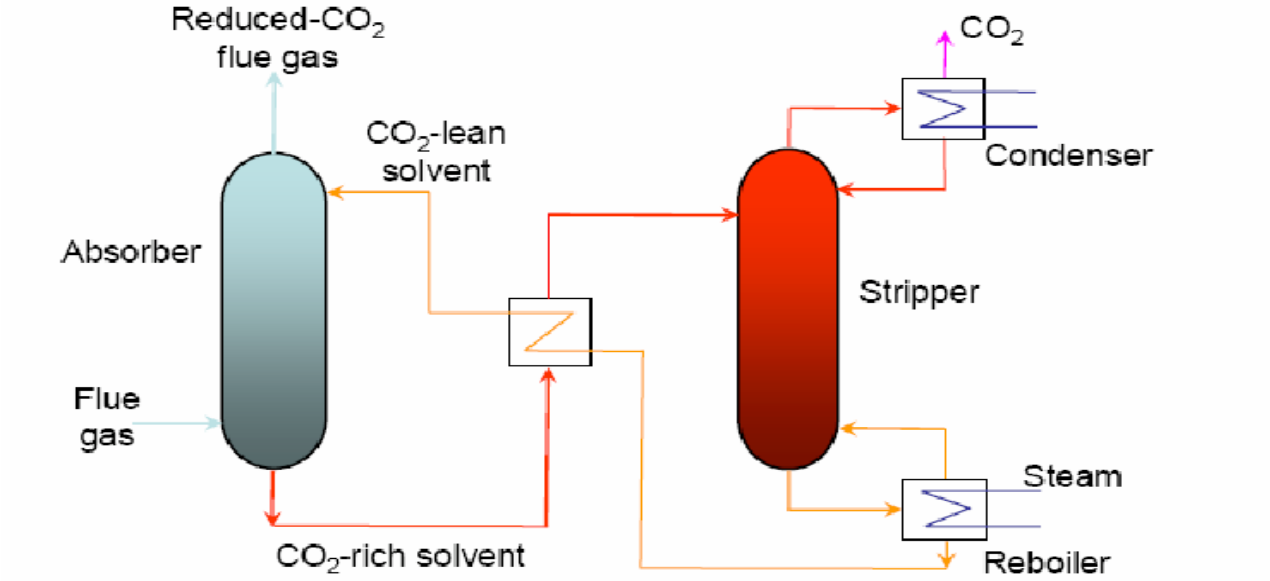


Fig. 3: Chemical scrubbing (Amine scrubbing) **Source:** [45].

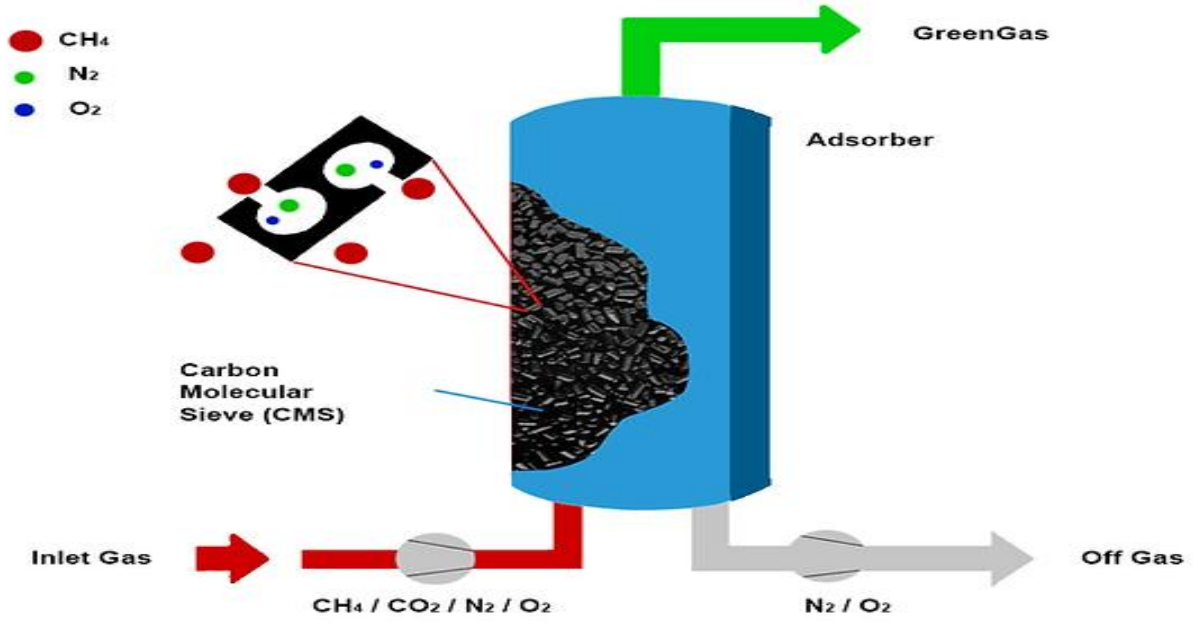


Fig. 4: Pressure Swing Adsorption (PSA) **Source:** [60].

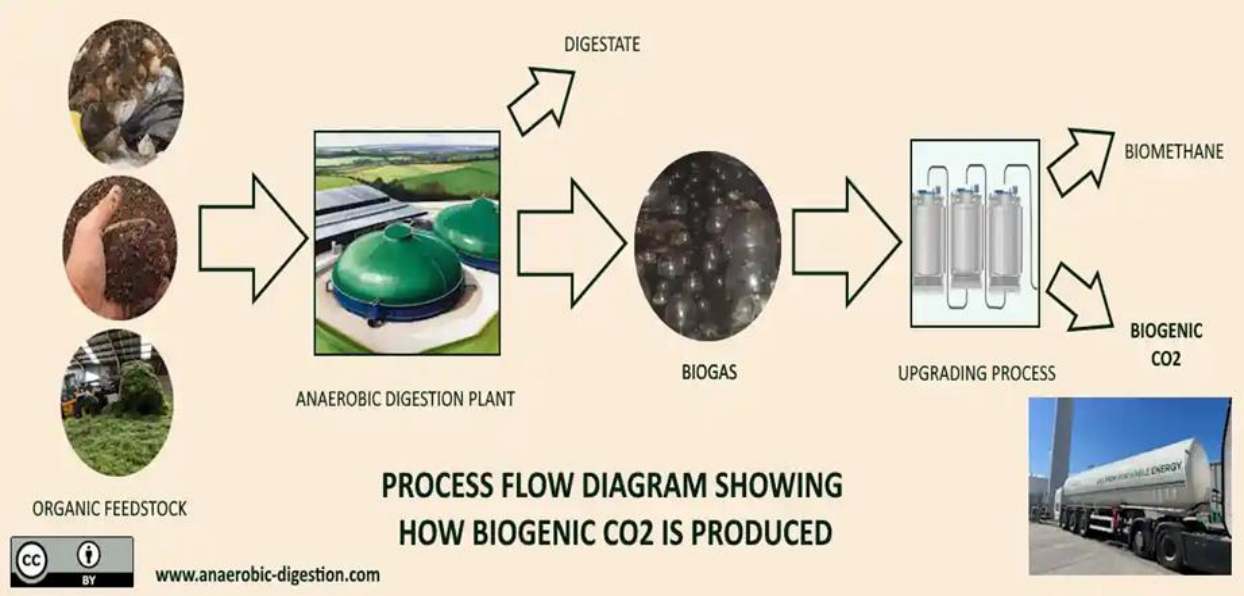


Figure 5: Process flow diagram showing the production process of biogenic CO_2

List of Tables

Table 1: Summary of the various direct air capture technologies

Technology	Evaluation	Advantage	Disadvantage	Cost	Technical maturity	Environmen effects
Chemical scrubbing (Amine scrubbing)	It is efficient for large-scale deployment where extensive level of purity is necessary [79].	It provides for excellent CO_2 capture, vast operational expertise and high biomethane purity [59].	The solvent's high regeneration energy requirement, the possibility of solvent deterioration, and equipment corrosion [105].	It requires high energy cost [10]	Commerci ally available and highly matured (TRL 9) [87].	Major effec include amı particulate, oc emissions Acidificatio eutrophicati soil/water contamination ozone format [36,72,80]
Pressure Swing Adsorption (PSA)	PSA is a practical, solid technology for biogas upgrading with lower energy consumption and corrosion resistance. It uses adsorbents like Zeolite 13X to separate CO_2 from methane under pressure cycles. Engineering evaluations centers on optimizing adsorbent materials (e.g., Metal-Organic	Biomethane purity >98%, biogenic CO_2 >99%, Low energy use, suitable for small-scale deployment, less operational complexity [1], [30].	Extensive energy demands for vacuum/compre ssors, Limited capacity [1].	High operating cost [52].	Readily available for commerci al deployme nt but research and developme nt focus on sorbent materials improvem ent [63].	High energy high water us and impurities

Table 2: Selected case studies of biogenic food-grade CO_2 capture and utilization

Region	Case study firm	Feedstock	Success in CO_2 capture and commercial utilization
Europe/Germany	Bioenergy Park Güstrow	Agriculture residues, animal manure, and organic waste.	The plant successfully produces approximately 18,000 tons of food-grade liquid CO_2 annually, which is captured during biomethane upgrading and purified for use in food and beverage applications [21].
Switzerland	Nesselnbach Biogas Plant	Food waste from household and restaurants	This facility processes about 300 tons of organic waste per day. CO_2 is extracted during biomethane production, purified to food-grade quality, and sold to an industrial gas supplier for applications such as beverage carbonation and dry ice production [38].
Denmark	Nature energy (Korskro biogas plant)	Animal manure and industrial/food organic waste.	The Korskro plant implemented a multi-step CO_2 purification process to capture CO_2 from biogas production that would otherwise be emitted. The purified CO_2 is upgraded to food-grade quality for the beverage industry, supporting circular bioeconomy initiatives [96,38].
Europe/United Kingdom	HappyDrink	By-products of ethanol fermentation	The company supplies food-grade CO_2 for the catering and beverage sector, including fast-food chains. Its system ensures a reliable supply for carbonation systems, enabling continuous dispensing without frequent cylinder replacements [39].