Activated Carbon from Lignocellulosic Biomass for Biogas Upgrading: Structure, Activation, and Adsorption Mechanisms

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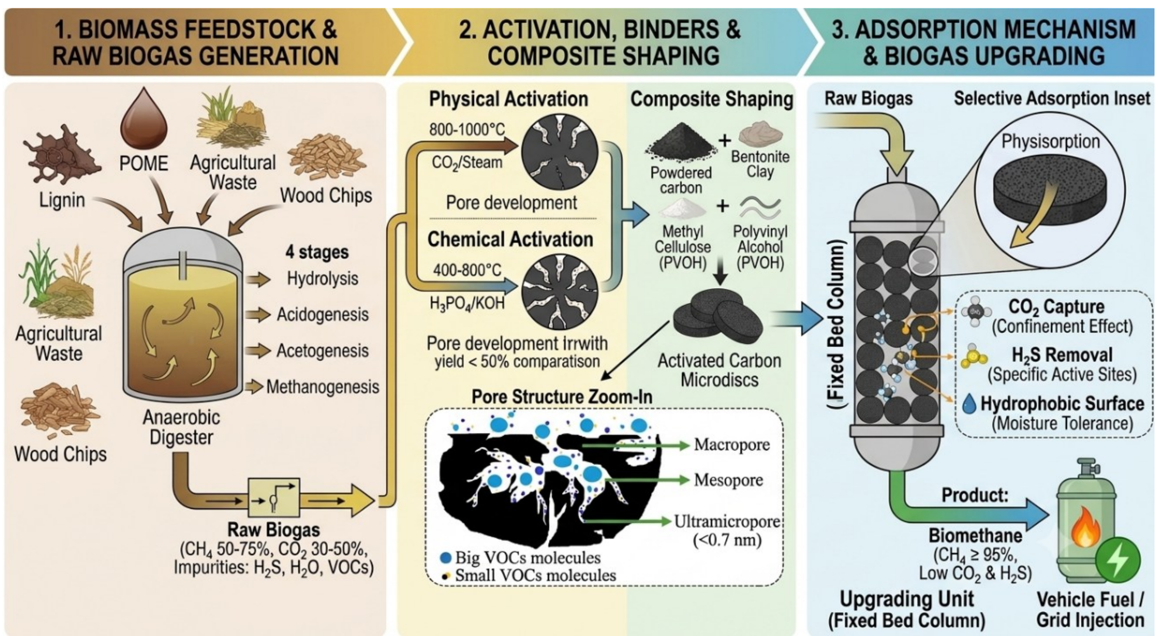
GRAPHICAL ABSTRACT



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Biogas produced through the anaerobic digestion of organic biomass is a renewable energy source with significant potential to replace fossil fuels. However, impurities such as carbon dioxide, hydrogen sulfide, and water vapor reduce its calorific value and cause operational challenges. Upgrading is therefore essential to increase methane concentration and biogas quality. Among various upgrading technologies, adsorption using activated carbon offers a practical, low cost, and energy efficient alternative. Activated carbon derived from lignocellulosic biomass exhibits high surface area (up to 3000 m²/g), tunable pore structure, and resistance to moisture saturation, making it suitable for carbon dioxide and methane separation. Activation techniques, both physical (using carbon dioxide or steam) and chemical (using potassium hydroxide or phosphoric acid), significantly influence surface functional groups and pore distribution. Natural and synthetic binders such as bentonite clay, methyl cellulose, and polyvinyl alcohol can enhance mechanical strength and adsorption stability in humid conditions. This review considers the structure, activation, and adsorption mechanisms of biomass derived activated carbon for biogas purification. Future research directions include hybrid composite development, functional surface modification, and performance evaluation under industrial biogas conditions. Overall, activated carbon represents a sustainable and efficient adsorbent supporting the transition toward cleaner and low carbon energy systems.

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Keywords: Biogas upgrading; Activated carbon; Adsorption; Renewable energy; Sustainable materials

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INTRODUCTION

Biogas is classified as a second-generation biofuel derived from the anaerobic digestion of biomass through a series of biochemical reactions involving various microorganisms in the absence of oxygen (Laçın *et al.* 2023). The composition of biogas depends largely on the type of biomass substrate used during the digestion process. Similarly, biogas is also naturally generated in landfills through anaerobic degradation, commonly referred to as landfill gas (Durán *et al.* 2018).

According to Werkneh (2022), biogas is produced by a wide range of anaerobic microbial communities that are capable of decomposing organic matter under controlled anaerobic conditions of moisture, temperature, and pH. These microorganisms facilitate the transformation of organic substrates into a high-energy gaseous fuel. The resulting biogas typically comprises approximately 50% to 70% methane (CH_4) and 30% to 50% carbon dioxide (CO_2). Methane serves as the primary energy carrier, whereas carbon dioxide represents a byproduct of the anaerobic digestion process (Pertiwiningrum *et al.* 2022).

In practical applications, biogas is most commonly utilized through decentralized combined heat and power (CHP) systems. In such systems, the biogas is first subjected to drying and desulfurization before being fed into a gas engine that drives a generator to produce both electricity and heat (Mertins and Wawer 2022). Furthermore, the utilization of biogas has been reported to exhibit functional similarities to natural gas, which is widely used for domestic heating, cooking, and as a vehicular fuel, thereby offering a renewable and sustainable alternative to fossil-based energy sources (Singh *et al.* 2023).

This review examines the potential and recent developments in biogas purification and upgrading processes, with particular emphasis on the role of biomass-derived activated carbon as an effective adsorbent for enhancing biogas quality.

Although activated carbon has been widely reviewed for general adsorption and environmental remediation applications, dedicated reviews focusing specifically on lignocellulosic biomass-derived activated carbon for biogas upgrading remain limited. In particular, the relationships among biomass precursor type, activation strategy, pore structure development, humid gas performance, and CO_2/CH_4 separation efficiency have not been critically consolidated. Therefore, this review addresses these gaps while providing updated perspectives relevant to biomass-rich regions such as Malaysia.

Biogas Production

The following section discusses the anaerobic digestion (AD) process that underpins biogas generation. Biogas is produced primarily through the anaerobic digestion of organic biomass, a well-established biological process that converts complex organic matter into a renewable and sustainable energy source. This technology serves as an environmentally friendly alternative to fossil fuels, offering the dual benefits of waste reduction and energy recovery (Thiruketheeswaranathan and Dharshayini 2021). Anaerobic digestion involves a multistage biochemical conversion process, consisting of four main phases: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Each stage involves distinct microbial consortia that operate in syntrophic association under strictly anaerobic conditions, collectively enabling the sequential degradation of organic matter (Raja and Wazir 2017).

Hydrolysis

During the hydrolysis phase, complex organic macromolecules such as carbohydrates, proteins, and lipids are broken down into soluble monomers including sugars, amino acids, and fatty acids (Menzel *et al.* 2020). Hydrolytic microorganisms secrete a wide range of extracellular enzymes such as cellulase, cellobiase, xylanase, amylase, lipase, and protease that catalyze the depolymerization of these compounds into simpler, soluble forms (Raja and Wazir 2017). This initial breakdown increases substrate accessibility for subsequent microbial metabolism. A diverse community of microorganisms participates in this stage, including strict anaerobes such as *Bacteroides, Clostridia,* and *Bifidobacteria,* as well as facultative anaerobes such as *Enterobacteriaceae* and *Streptococci,* which help initiate the digestion process (Raja and Wazir 2017).

Acidogenesis

Following hydrolysis, acidogenic bacteria convert the soluble hydrolysis products into short-chain volatile fatty acids (VFAs), such as acetic, propionic, formic, and lactic acids. In addition, alcohols (ethanol and methanol) and ketones (glycerol and acetone) may also be produced. This phase generates byproducts including carbon dioxide (CO_2), hydrogen (H_2), and ammonia (NH_3) (Uddin and Wright 2023). The acidogenesis stage establishes a critical link between the breakdown of complex substrates and the formation of simpler intermediates required for subsequent methane production.

Acetogenesis

During acetogenesis, acetogenic bacteria (acetogens) further metabolize the VFAs produced in the acidogenic stage into acetic acid, hydrogen, and carbon dioxide (Muthudineshkumar and Anand 2018; Anukam *et al.* 2019). These reactions are essential for supplying substrates that methanogenic archaea utilize in the final phase of anaerobic digestion. As reported by Raja and Wazir (2017), acetogenesis marks the transition point at which biomass-derived intermediates become directly available for methane formation.

Methanogenesis

The final stage, methanogenesis, is where methane (CH_4) is generated from the intermediate products formed in earlier stages (Uddin and Wright 2023). Methanogenic archaea, such as *Methanococcus voltae* and *Methanococcus vannielli*, convert acetic acid (CH_3COOH) and hydrogen (H_2) into methane and carbon dioxide. These microorganisms are obligate anaerobes and are highly sensitive to even trace levels of oxygen (Anukam *et al*. 2019; Laçın *et al.* 2023). Methanogenesis determines the overall yield and composition of biogas, as methane constitutes the primary energy-bearing component. The efficiency of each stage directly influences the composition and quality of biogas produced, thereby determining the requirements for subsequent upgrading and purification processes.

Biogas Composition, Production, and Upgrading and Impurities

Biogas composition and impurities

Biogas generated through the anaerobic degradation of biodegradable waste or wastewater primarily comprises methane (CH_4) and carbon dioxide (CO_2), accompanied by minor components such as hydrogen sulfide (H_2S), water vapor, siloxanes, ammonia (NH_3), and volatile organic compounds (VOCs). The exact composition of biogas varies depending on the type and origin of the feedstock as well as the operating conditions within the digester (Werkneh 2022).

Table 1. Typical Composition of Biogas from Different Feedstocks

Feedstock Type	CH_4 (%)	CO_2 (%)	H_2S (ppm)	N_2 (%)	Reference
Palm Oil Mill Effluent (POME)	50-75	30-40	10-2000	<2	Fahrudin *et al*. (2024); Thong-nuekhaeng and Onthong (2011)
Food Waste	50-75	25-50	0-1000	<3	Huang *et al*. (2017)
Animal Manure	35-75	15-60	50-2000	<2	Dussadee *et al*. (2022); Marin *et al*. (2020)
Municipal Sludge	35-75	25-50	100-10000	<2	Sihlangu *et al*. (2024); (Hernández *et al*. (2021); Banerjee *et al*. (2021)
Landfill Gas	50-60	40-50	10-2000	0.5-5	Duan *et al*. (2021); Arvola *et al*. (2012)

According to Wasajja *et al.* (2020), exceeding the recommended concentrations of these impurities can cause serious operational challenges, particularly in thermal and catalytic biogas conversion systems. Furthermore, the uncontrolled release of such impurities, especially hydrogen sulfide and siloxanes, into the atmosphere may lead to environmental pollution and health hazards. Therefore, understanding the composition of biogas is essential to determine the appropriate upgrading and purification strategies to achieve high efficiency and environmental safety.

Feedstock → Anaerobic Digestion → Raw Biogas (CH_4, CO_2, H_2S, H_2O) → Cleaning → Upgrading → Biomethane $CH_4 \geq 95\%$) → Utilization (Power/Vehicle Fuel)

Fig. 1. Schematic illustration of the general process flow for biogas generation, purification and upgrading into biomethane

Biogas production in Malaysia

In Malaysia, the primary feedstock used for biogas production is palm oil mill effluent (POME), which accounts for about 93% of the national feedstock supply, followed by landfill gas at 5%, and other sources such as manure, bagasse, and sewage sludge (Lim *et al.* 2021). POME is highly suitable for anaerobic digestion because of its high organic content and good biodegradability. A BOD/COD ratio of approximately 0.5 indicates that POME is readily biodegradable, making it well suited for biological treatment processes, particularly anaerobic digestion for methane production. Where recalcitrant organic compounds are present, physical or chemical pretreatment can be applied before biological treatment to enhance hydrolysis, improve substrate biodegradability, reduce potential inhibitory effects, and ultimately increase methane yield (Seng and Madaki 2013).

Biogas plants in Malaysia mainly employ two reactor configurations: covered lagoon systems and continuous stirred tank reactors (CSTRs), also known as closed anaerobic digester tanks (Lim *et al.* 2021). These systems are designed to handle the characteristics of POME while optimizing methane production. Expanding biogas production from palm oil industry waste provides significant potential for Malaysia to strengthen its renewable energy sector and reduce greenhouse gas emissions.

Upgrading technologies

The objective of biogas upgrading is to separate methane from carbon dioxide and other gaseous impurities, thereby increasing its heating value and enabling its use as biomethane, a renewable alternative to natural gas (Ahmed *et al.* 2021; Pevida and Rubiera 2023). The upgrading process generally involves two stages. The first is cleaning, which removes toxic and corrosive compounds such as hydrogen sulfide and siloxanes. The second is upgrading, which increases the methane concentration by decreasing the carbon dioxide levels.

According to the Contractor Report to the California Energy Commission (Ong *et al.* 2014), biogas upgrading is essential for applications such as natural gas pipeline injection and vehicle fuel use. Commonly commercialized technologies include pressure swing adsorption, chemical solvent scrubbing using amines, and pressurized water scrubbing. Newer alternatives such as membrane separation and cryogenic distillation are emerging to improve upgrading efficiency and lower operating costs. However, despite their high performance, most of these systems require substantial capital investment and involve relatively high operational expenses (Mulu *et al.* 2021).

Among the various upgrading approaches, adsorption-based systems using carbonaceous materials have gained attention because activated carbon can be produced from low-cost agricultural residues. At the same time, regeneration energy is generally lower than that of solvent scrubbing systems. Biomass-derived activated carbon production costs have been reported to be significantly lower than those of advanced adsorbents such as MOFs, improving the economic feasibility of decentralized biogas plants.

Activated Carbon for Biogas Upgrading

Various solid sorbents have been explored for carbon dioxide (CO_2) removal from biogas, including zeolites, activated carbon, calcium oxides, hydrotalcites, supported amines, and metal organic frameworks (MOFs). Among these, zeolites have received extensive attention because of their high CO_2 selectivity, thermal stability, and pressure resistance (Gil *et al.* 2015).

However, for CO_2 and methane separation using adsorption, recent studies have increasingly focused on carbon-based adsorbents due to their adjustable pore structure and cost effectiveness (Vilella *et al.* 2017). As reported by Vilella *et al.* (2017), activated carbon offers advantages such as hydrophobicity, which prevents deactivation by water saturation, low heat of adsorption that facilitates regeneration, and relatively low cost. Similarly, Durán *et al*. (2018) demonstrated that activated carbon performs effectively for biogas purification even under humid conditions because of its low affinity for water and stable adsorption capacity over repeated use. These characteristics make activated carbon one of the most promising and economical adsorbents for biogas upgrading applications.

For example, zeolites commonly exhibit CO_2 capacities of 3 to 5 mmol/g under ambient conditions but are moisture-sensitive, whereas activated carbons typically show 2 to 4 mmol/g CO_2 capacities with superior water tolerance and easier regeneration. MOFs may exceed 5 mmol/g under optimized conditions, but their higher synthesis cost and stability concerns remain barriers to widespread industrial adoption (Song *et al.* 2022)

Historical development

Activated carbon has been used for purification purposes since ancient times and later developed into an industrial adsorbent during the nineteenth and twentieth centuries (Chew *et al.* 2023; Muttil *et al.* 2017). Today, it is widely applied in water treatment, gas purification, catalysis, and energy storage (Akram *et al.* 2022)

Structural and physicochemical properties

Activated carbon, also known as activated charcoal, is an amorphous, highly porous carbonaceous material characterized by a large surface area and well-developed pore structure. It is typically derived from natural precursors such as wood, coal, coconut shells, and peat (Chew *et al.* 2023; Neolaka *et al.* 2023). The activation process, involving high-temperature treatment with activating agents such as steam or carbon dioxide, produces an intricate pore network and enhances its surface area.

Although high BET surface area (300 to 3500 m^2/g) is often desirable, adsorption performance depends more critically on pore size distribution, ultramicropore volume, and surface chemistry (Fourqoniah *et al.* 2023). For CO_2 capture, carbons enriched with narrow micropores frequently outperform materials with higher total surface area but wider pore structures. According to Bubanale and Shivashankar (2017), pore widths vary from sub-nanometer to several thousand nanometers, allowing the material to efficiently remove impurities across different phases (Fig. 2).

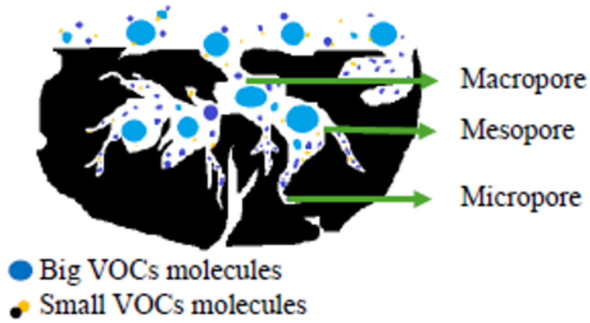

Fig. 2. Pore structure of activated carbon; Source: James *et al.* (2025)

Synthesis and activation methods

The preparation of activated carbon involves two primary stages: carbonization and activation. During carbonization, the precursor undergoes thermal decomposition at 400 to 800 °C in an inert atmosphere, typically nitrogen, to form char while preventing oxidation (Neolaka *et al.* 2023). The resulting char is then subjected to activation to develop porosity and enhance its surface area (Ganjoo *et al.* 2023).

Physical activation

Physical activation uses gases such as steam or carbon dioxide at temperatures between 800 and 1000 °C to enlarge and develop the pore structure (Bubanale and Shivashankar 2017). Steam primarily widens micropores, whereas CO_2 enhances microporosity during the early stages of activation (Ahmad *et al.* 2013). CO_2 is frequently preferred for its simplicity and cleanliness in operation, making it suitable for large-scale processing.

Chemical activation

Chemical activation is a one-step process that combines chemical impregnation and carbonization. Chemical agents such as potassium hydroxide (KOH), sulfuric acid (H_2SO_4), sodium hydroxide (NaOH), zinc chloride ($ZnCl_2$), and phosphoric acid (H_3PO_4) are employed within the range 500 to 900 °C under oxygen-free conditions (Muttil *et al.* 2023). These activating chemicals promote pore formation, minimize tar generation, and increase product yield.

Chew *et al.* (2023) reported that phosphoric acid (H_3PO_4) is commonly used in biomass-based activation because it produces high micropore volumes, low ash content, and large surface areas. Potphode *et al.* (2020) and Benaoune *et al*. (2025) highlighted the effectiveness of phosphoric acid (H_3PO_4) compared to other agents (H_3PO_4, H_2SO_4, $ZnCl_2$, $FeCl_3$, NaOH, KOH, and K_2CO_3), showing that it yields activated carbon with substantial surface areas (456 to 2810 m^2/g), decent yields (26.1% to 85%), and versatile adsorption capacities (2.5 to 89.3 mg/g) for practical applications.

Overall, chemical activation provides higher yields and better pore development at lower temperatures and shorter processing times compared to physical activation. Nevertheless, physical activation produces cleaner carbon surfaces and more uniform pore distribution (Chew *et al.* 2023; Muttil *et al.* 2023).

To produce high-performance activated carbon from lignocellulosic biomass, the selection of activation method is a critical factor because it directly influences pore development, surface chemistry, product yield, processing cost, and overall adsorption performance. The two most widely employed approaches are physical activation and chemical activation, each offering distinct advantages and limitations in terms of efficiency, scalability, and environmental impact. A comparative summary of these methods is presented in Table 2.

Table 2. Comparison of Physical and Chemical Activation Methods for Biomass-Derived Activated Carbon

Parameter	Physical Activation	Chemical Activation	Reference
Temperature	800 to 1000°C	400 to 800°C	Abdulsalam *et al.* 2019
Activating agent	Steam, CO_2	Chemical uses acids/bases KOH, H_3PO_4, K_2CO_3, HCl, NaOH, $ZnCl_2$	Ahmad *et al.* 2024; Mashhadimoslem *et al.* 2021; Yi *et al.* 2022 Abdulsalam *et al.* 2019; Bergna *et al.* 2018
Surface area	Moderate-high	High Up to ~2000 m^2/g	Blankenship and Mokaya 2022; Mashhadimoslem *et al.* 2021
Yield	Lower (~6wt.%)	Higher (27-47wt.% than physical)	Nicolae *et al.* 2020; Bergna *et al.* 2018
Cost	Cheaper in reagents but may incur higher energy	More complex and costly due to reagents	Rajan and Anish 2024; Mashhadimoslem *et al.* 2021
Washing required	Minimal	Yes More washing to remove residue/neutralization	Kim *et al.* 2023; Mashhadimoslem *et al.* 2021
Environmental issue	Environmentally friendly conditions	Chemical wastewater	Qiu *et al.* 2023; Yi *et al.* 2022
Industrial scalability	Simpler and more economical	Feasible with two-step activation	Qiu *et al.* 2023; Purhanudin *et al.* 2022

In industrial systems, adsorption performance is strongly influenced by operating pressure, temperature, gas flow rate, relative humidity, and contact time. Elevated pressure generally increases CO_2 uptake, whereas high temperature reduces physisorption capacity. Water vapor may compete with CO_2 for adsorption sites depending on adsorbent surface polarity. Therefore, process optimization is essential for stable long-term biogas upgrading (Santoni *et al.* 2023; Poser *et al.* 2023).

Adsorption mechanism

Adsorption refers to the accumulation of molecules from a gas or liquid onto a solid surface, forming an interfacial layer (Alaqarbeh *et al.* 2021). The adsorbate refers to the substance being captured, while the solid phase acts as the adsorbent. Depending on the system, adsorption can occur in gas–solid, liquid–solid, liquid–liquid, or gas–liquid interfaces.

In solid–gas and solid–liquid systems, the interfacial layer model is commonly applied to describe molecular adhesion. In biogas upgrading applications, physical adsorption (physisorption) is dominant, where the weak Van der Waals forces attract gas molecules to the surface of the adsorbent without altering their chemical composition (Alaqarbeh *et al.* 2021).

Vilella *et al.* (2017) reported that adsorption-based systems are favored for gas purification, biogas upgrading, and CO_2 capture due to their low energy demand and cost-effectiveness. Activated carbon, being carbon-based and highly porous, is one of the most effective adsorbents for CO_2/CH_4 separation. Accordingly, the activated carbon microdiscs developed in this study are designed to utilize this adsorption mechanism for biogas upgrading purposes.

Micropores (<2 nm) are primarily responsible for CO_2 adsorption due to enhanced pore-filling interactions and overlap of adsorption potentials. Ultramicropores (<0.7 nm) are especially effective for CO_2 capture because the kinetic diameter of CO_2 (0.33 nm) allows strong confinement effects (Xie *et al.* 2020). Mesopores (2 to 50 nm) contribute mainly to diffusion and transport of gas molecules toward active adsorption sites. Surface oxygen-containing groups and nitrogen functionalities may further enhance CO_2 affinity through dipole–quadrupole interactions, while hydrophobic graphitic surfaces improve performance under humid biogas conditions (Fingolo *et al.* 2020).

Although physisorption is the dominant mechanism in conventional activated carbon, chemisorption may also contribute when oxygenated functional groups, nitrogen functionalities, or impregnated alkaline/metal species are present on the carbon surface (Awogbemi and Desai 2025). These active sites can enhance selective interactions with acidic gases such as CO_2 and H_2S (Adegoke *et al.* 2025).

Adsorption equilibrium data are commonly interpreted using Langmuir and Freundlich isotherm models. The Langmuir model assumes monolayer adsorption on homogeneous active sites, whereas the Freundlich model describes multilayer adsorption on heterogeneous surfaces. These models are widely applied to evaluate CO_2 uptake capacity and adsorption affinity of biomass-derived activated carbons (Kumar *et al.* 2025). These models also enable comparison of adsorption performance across different adsorbents and provide insight into surface heterogeneity and adsorption mechanisms.

Binder composition

Binding agents play a crucial role in shaping and stabilizing activated carbon structures, providing mechanical strength, cohesion, and uniform porosity. In the fabrication of activated carbon (AC) microdiscs, the binder system must not only ensure structural integrity but also support adsorption activity and compatibility with biogas upgrading environments. This section presents an overview of the selected binders such as bentonite clay, methyl cellulose, and polyvinyl alcohol emphasizing their structural roles, functional characteristics, and synergistic contributions to AC microdisc formation.

Bentonite clay

Bentonite clay (BC) has been used by humans since prehistoric times due to its diverse physicochemical characteristics and therapeutic applications. In modern applications, BC exhibits valuable properties such as high adsorption capacity, swelling potential, and cation exchange capability. According to Lasich (2020), bentonite is a clay mineral composed primarily of crystalline montmorillonite and is abundantly found in South Africa. It has broad industrial applications, including as a protein adsorbent in food and beverage industries, a foundry binder, and as drilling mud in the oil and gas sector.

Recent research by Borah *et al.* (2022) found that BC possesses a large surface area due to its structural similarity to montmorillonite, and its functionality can be improved by increasing its total surface area. Bentonite clay also exhibits high cation exchangeability, allowing various cations to be incorporated into its structure. Hosterman and Patterson (1992) reported that the adsorption capacity of bentonite can be further improved by calcination at temperatures between 400 and 1000 °C, followed by crushing and screening to achieve the desired granule size.

Methyl cellulose

Methyl cellulose (MC) is a chemically modified derivative of cellulose in which hydroxyl (-OH) groups on the cellulose backbone are partially substituted by methoxyl (-OCH_3) groups (Hynninen *et al.* 2021). This substitution imparts water solubility and thermoresponsive behavior, distinguishing MC from other cellulose derivatives. Aqueous MC solutions exhibit a reversible lower critical solution temperature (LCST) behavior, transitioning from a transparent solution to a turbid gel upon heating above approximately 40 °C, and returning to a fluid state upon cooling. This gelation process is associated with the transformation of MC polymer chains from random coils into fibrillar aggregates (Hynninen *et al.* 2021).

Methyl cellulose provides a physically crosslinked, thermosensitive water-based matrix, where its stiffness can be tuned from viscous to rigid gel by adjusting polymer concentration and temperature. Owing to its biocompatibility, non-toxicity, and rheological versatility, MC is widely used as a viscosity modifier, stabilizer, and functional ingredient in food technology, pharmaceuticals, and biotechnology (Hynninen *et al.* 2021).

Furthermore, Nasatto *et al.* (2015) reported that MCs are soluble in water, mixed solvents (water/ethanol), and various organic solvents. They are non-ionic polymers that can form compatible blends with other polymers such as polyvinyl alcohol (PVOH), salts, and other additives. The MC also prevents sedimentation by facilitating uniform particle dispersion. Its ability to blend with PVOH enables the formation of porous composite structures.

Polyvinyl alcohol

Polyvinyl alcohol (PVOH) is a water-soluble synthetic polymer with the idealized chemical formula $[CH_2CH(OH)]_n$. According to Feldman (2020), PVOH is produced by the hydrolysis of polyvinyl acetate (PVAc) and is widely utilized in various applications including fiber production, artificial leather, tubing, gaskets, adhesives, emulsifiers, and coatings. It is valued for its stability, flexibility, and resistance to oil derivatives, as well as its excellent film-forming capabilities.

PVOH is recognized as a biodegradable and environmentally friendly alternative to conventional synthetic polymers such as polyethylene or polypropylene. As highlighted by Feldman (2020), biopolymers including PVOH, MC, starch, dextran, and carrageenan serve as promising substitutes for non-biodegradable plastics. PVOH's advantages include low cost, high film strength, flexibility, and the presence of abundant hydroxyl groups that enhance hydrogen bonding and compatibility with other polymers.

Due to these attributes, PVOH is frequently used as a host polymer in composite formulations. Its high chain flexibility and polar hydroxyl groups facilitate effective blending with MC and carbonaceous materials. In the current formulation, PVOH serves as a supportive organic binder to improve the cohesive strength, film integrity, and uniformity of the AC microdiscs during shaping and drying.

To utilize powdered activated carbon in practical packed-bed or pressure swing adsorption systems, shaping agents or binders are often required to improve particle cohesion, mechanical durability, and handling properties. Common binders used in activated carbon composites are summarized in Table 3.

Table 3. Functional Characteristics of Binders Materials for Shaped Activated Carbon

Binder Type	Nature	Key Functional Properties	Role in AC Composite	Advantages	Reference
Bentonite Clay	Inorganic	Swelling ability. cation exchange capacity, structural rigidity	Enhances mechanical stability and pellet strength	High thermal stability, low cost	Lasich (2020); Borah *et al.* (2022)
Methyl Cellulose	Organic	Thermoreversible gelation, viscosity control, water solutbility	Acts as dispersion and rheology modifier during shaping	Biodegradable, non-toxic, good film-forming behavior	Hynninen *et al.* (2021
Polyvinyl Alcohol	Synthetic	High flexibility, film forming ability, adhesive strength	Improves cohesion, adhesion, and porosity retention	Cost-effective, durable, water soluble	Feldman (2020)

Industrial Application Status and Scale-Up Challenges

Biomass-derived activated carbon has been investigated for fixed-bed adsorption columns, pressure swing adsorption (PSA), and H_2S polishing units in decentralized biogas plants. Particularly in palm oil mill biogas systems, activated carbon offers a low-cost route for gas purification (Blankenship and Mokaya 2022).

However, several scale-up barriers remain, including; variability of biomass feedstock quality, high drying and pretreatment cost, reduced adsorption after repeated regeneration cycles, pellet attrition under gas flow, and moisture competition in raw biogas streams. Potential solutions standardized feedstock preparation, pelletized composite adsorbents, waste-heat regeneration, and hybrid adsorption-membrane systems (Shi *et al.* 2025).

CONCLUSION AND FUTURE OUTLOOK

Biogas upgrading is a critical step in enhancing the energy value and applicability of this renewable resource. Traditional upgrading methods, while effective, often suffer from high costs and complex operational requirements. Activated carbon has emerged as a promising alternative owing to its abundance, cost effectiveness, high surface area, and tunable porosity. Its hydrophobic nature and resilience under humid conditions further strengthen its suitability for large scale biogas purification. Advances in activation techniques and the integration of natural and synthetic binders have expanded its applicability, improving structural integrity and adsorption efficiency.

Despite substantial progress in the use of activated carbon for biogas upgrading, several challenges remain to be addressed to achieve industrial scalability and sustainability. The variability of feedstock characteristics, the presence of trace impurities, and the regeneration efficiency of adsorbents continue to influence the long-term feasibility of the process. Therefore, future studies should focus on developing tailor engineered activated carbons with enhanced surface functionality and selectivity toward specific gas components, particularly carbon dioxide and hydrogen sulfide.

Integration of bio-based precursors, such as lignin, bamboo biomass, or oil palm residues, offers a sustainable route for producing high performance activated carbon while simultaneously valorizing agricultural waste. Additionally, the coupling of adsorption-based upgrading with other purification technologies, including membrane separation or cryogenic distillation, could lead to hybrid systems with superior efficiency and reduced energy input.

Advancements in computational modeling and in situ characterization will further enable a deeper understanding of gas–solid interactions within porous matrices, supporting the rational design of next generation adsorbents. Ultimately, a holistic approach combining material innovation, process optimization, and environmental assessment will be crucial in advancing activated carbon-based biogas upgrading technologies toward full commercial implementation. Taken together, activated carbon represents a sustainable pathway for biogas upgrading, supporting global efforts to expand renewable energy utilization and mitigate reliance on fossil fuels.

Future commercialization will depend on balancing adsorption performance, regeneration efficiency, and production cost. Malaysia possesses strong potential due to abundant palm biomass resources that can be valorized into high-value activated carbon adsorbents.

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