

Research Progress on Carbon Dioxide Capture, Utilization and Storage Technology

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Abstract. The escalating climate crisis, driven primarily by the enhanced greenhouse effect, has made carbon dioxide (CO₂) a central focus of global scientific and political discourse. As the primary long-lived greenhouse gas emitted from human activities—such as fossil fuel combustion, industrial processes, and deforestation—CO₂ concentrations in the atmosphere have reached high levels. This rapid accumulation is unequivocally linked to global warming, rising sea levels, and an increased frequency of extreme weather events. While transitioning to renewable energy and enhancing energy efficiency remain crucial mitigation strategies, their progress has been insufficient to meet international climate targets. Consequently, Carbon Capture, Utilization, and Storage (CCUS) technologies have emerged as an essential complementary approach to directly reduce atmospheric CO₂ and achieve net-zero emissions. Through a comprehensive literature review, this paper examines the principles, efficiency, energy consumption, and economic feasibility of major CCUS approaches, including physical adsorption, chemical absorption, membrane separation, and biological fixation. The analysis reveals that each method possesses distinct advantages and limitations. For instance, chemical absorption is well-established but energy-intensive, while biological processes are eco-friendly yet limited by scalability and slow kinetics. Future advancements should focus on material innovation, process integration, and energy optimization to enhance capture efficiency, reduce costs, and ensure operational safety. This study offers a comparative perspective to support the selection and development of CCUS technologies, contributing to carbon neutrality goals and sustainable energy transitions.

Keywords: CO₂ capture, CO₂ storage, CCUS technology, carbon neutrality

1. Introduction

Nowadays, the enhanced greenhouse effect and global warming have become critical issues discussed by scientists across various disciplines. As global temperatures continue to rise, the urgency to address this climate crisis has never been greater. The greenhouse effect is primarily caused by greenhouse gases that form a layer in the atmosphere, trapping heat and preventing it from escaping into space. Common greenhouse gases are methane (CH₄), carbon dioxide (CO₂), and nitrous oxides. With the continuous increase in emissions, especially of CO₂, the enhanced greenhouse effect is accelerating climate change at an alarming rate. This has led to severe

consequences, particularly in less economically developed countries, where communities are experiencing economic instability, food shortages, and water scarcity.

Carbon dioxide is especially concerning due to its long atmospheric lifetime and significant role in driving climate change. Major sources of CO₂ emissions include industrial activities, which have been the largest contributors since the Industrial Revolution, as well as transportation and energy production from fossil fuels. According to the report of CO₂ emission in 2023 by IEA, global energy-related carbon dioxide (CO₂) emissions reached a record high of 37.4 billion tonnes (Gt). This represents an increase of 1.1% (or 410 million tonnes) compared to 2022 levels [1].

Previous efforts to mitigate climate change have largely focused on reducing carbon emissions by transitioning away from fossil fuels through renewable energy sources, reforestation, and population control. However, progress has been slow, and these measures alone have proven insufficient. For instance, despite the rapid growth of wind and solar power, fossil fuels still account for over 80% of global energy consumption. Moreover, the concentration of CO₂ in the atmosphere has increased by 23% over the past 125 years due to both human activities and natural processes. Karazsia's research have already suggested that public anxiety and growing awareness of the need for more effective solutions are spreading globally [2].

Carbon Capture, Utilization, and Storage (CCUS) has emerged as a promising complementary strategy. First developed in the 1960s [3], CCUS technologies are now gaining attention across scientific fields including chemistry, biology, and geology. The process involves capturing CO₂ emissions from large point sources like power plants or directly from the air, converting them into useful products (such as biofuels or building materials), and securely storing them underground or in other long-term reservoirs to prevent re-entry into the atmosphere. The International Energy Agency (IEA) highlights that CCUS could contribute to reducing global CO₂ emissions by nearly 15% by 2050 [4].

However, CCUS also contains limitations. Reasonable economic cost, applicable scale, social acceptance, and potential ecological impacts still remain as main concerns in implementing CCUS. Therefore, a clear and objective comparative analysis is critical to guide policymakers, scientists, and industry leaders in supporting the most sustainable and effective technologies for their region and country.

This paper aims to provide a comprehensive review and evaluation of major CCUS methods. Methods covered in this paper can be categorized into physical, chemical, and biological methods which come in different disciplines and have their own ideal application conditions. An evaluation of the advantages and limitations of each approach will then be conducted. Evaluation criteria include capture efficiency, energy consumption, operational cost, scalability, and long-term safety. While synthesizing current knowledge, this paper will also emphasize the need for further research. Innovative approaches—such as enhancing natural carbon sinks in oceans and soils—also demand deeper investigation. Ultimately, this study seeks to refine CCUS efficiency and unlock its full potential as a cornerstone of global climate action.

2. Source of CO₂ emission

In the synthesis report of IPCC on climate change in 2023, human activities are claimed accountable to causing global warming. Global greenhouse gas emissions have been rising continuously. Factors contributing to this increase include unsustainable energy use, land use and land-use change, lifestyles and patterns of consumption and production across regions, between and within countries, and among individuals [5].

2.1. Energy-related CO₂ emission

CO₂ emission from the energy generation sector mainly comes from burning fossil fuels. As suggested in the IPCC report, fossil fuel is an unsustainable energy source. Fossil fuel comes in solid, liquid, and gas form which is named correspondingly coal, oil, and natural gas. It is formed under intense pressure and heat underground from dead animal and plant remains at least 300-400 million years ago. This indicates the nonrenewable feature of fossil fuels. Fossil fuels that formed from carbon-rich remnants of organisms are also carbon-abundant. Therefore, combustion of fossil fuels lead to significant CO₂ emission. However, despite its clear drawbacks, the efficiency and accessibility of fossil fuels still make it the top energy source for countries, especially LEDC (less economically-developed countries). In the review article written by Akbari et al., electric power plant is held accountable for 30% of global carbon dioxide emission [6].

It is crucial to reduce fossil fuel use for generating electricity, but a lot of LEDC cannot afford a better energy source. Furthermore, some countries even rely on exporting fossil fuels to maintain national economy. As a result, more ways of reducing carbon dioxide concentration and slowing down its accumulation in the atmosphere are needed to alleviate pressure on reducing its emission.

2.2. Land use CO₂ emission

Another sector contributing to CO₂ emission is the AFOLU sector (Agriculture, Forestry, and Other Land Use). With increasing population, and increasing demand for food, more forest land is cleared for agricultural use. Trees are also cut down by means of urban expansion. Nowadays, the rate of which human cleans the forest exceeds the rate of forest growing back, resulting in deforestation and rapidly decrease the area of forest. This not only cause destabilization of ecosystems, but also affect CO₂ emission. There are mainly two ways Tanveer et al. listed in their research of how deforestation affects CO₂ emission [7]. When trees are cut down, the woods that are left over remains and are decomposed by bacteria. Decomposition of wood breaks it down to elements. As trees are typical carbon sinks, their decomposition process release carbon dioxide. Therefore, the more leftover wood humans produce when clearing forests, the more CO₂ emission deforestation contributes to global emission. If the leftover woods are burnt, its carbon storage also enters the atmosphere as carbon dioxide.

Yang et al. [8] discovered that not only the destruction of forest increase CO₂ emission, draining peatland can also emit carbon dioxide. Peatlands are water-logged areas that store massive amounts of carbon because the wet conditions slow decomposition. When drained for agriculture, the peat is exposed to air, decomposes rapidly, and releases enormous quantities of CO₂ over long periods. Fires on dried peatlands are particularly devastating and smoky.

Moreover, turning forest area into agricultural land furthermore contributes to CO₂ emission. Applying fertilizers during farming commonly adds organic matter, if these matters are not absorbed by crops or plants before its decomposition, emits carbon dioxide.

Yet food security is currently another urgent, ongoing global issue receiving attention globally. Regulation on fertilizer can be implemented, but people's appeal to food for maintaining life cannot be left unanswered. Apart from seeking balance in the AFOLU sector, new ways of dealing with greenhouse gases should be explored.

2.3. Consumption-related CO₂ emission

Consuming, or using, vehicles for transportation also lead to CO₂ emission. The petroleum used by gas cars contains fossil fuel. So, when the engine burns the petroleum for energy to move, the gas exhaust emitted from the car contains carbon dioxide. Expanding urban areas and increasing population all result in longer and more amount of vehicle ride. Although governments of MEDCs (more economically-developed countries) are promoting electrical vehicles to mitigate CO₂ emission from the transportation sector, the amount of carbon dioxide produced by vehicles are still increasing.

2.4. Production-related CO₂ emission

From the consumption side of the economy comes the production side. The process of producing certain products also involves emitting carbon dioxide in the industrial sector. As Akbari et al. claimed in their research, a crucial component of the fossil fuel importers is oil and petrolchemical industries. Products like plastics, paints, rubbers, and some protective material made by these industries through complex chemical process involving fossil fuels. The amount of carbon dioxide emitted in industrial process had 21% of the total CO₂ emission. Restriction of emissions are already passed to these industries, such as implementing carbon tax which limits the amount of carbon dioxide one industry can emit, and carbon budget, which stimulates transaction in economy while controlling the amount of emission. On the other hand, as long as there is profit, illegal trespassers exist. The trend of emission by petroleum product, like the others, also shows an increasing trend. New methods are needed in solving climate change, and this is where people turned their attention on CCUS.

3. Methods for carbon capture and storage

The main methods of CCS currently include physical, chemical, and biological process. In terms of physics, physical adsorption and absorption, membrane-based separation, hydrate-based carbon dioxide separation, and cryogenic distillation can capture carbon into the absorbent, either disperse them into the absorbent or adhere them on the surface of the absorbent. Chemical methods include chemical absorption and chemical looping. These methods utilize the chemical properties of different substances to react with carbon and capture it. Finally, there is biological pathways, including biological separation, which can be further divided into photosynthetic and non-photosynthetic methods.

3.1. Physical separation methods

Physical separation methods include physical adsorption, physical absorption, membrane-based separation, hydrate-based separation, and cryogenic distillation. It does not include any conversion of carbon dioxide into another substance. For this reason, it is crucial to keep in mind that the recovery of carbon dioxide for the “utilization” step in CCUS are generally easier in physical separation methods. Chemical and biological methods, on the other hand, involve reactions that transfer carbon in carbon dioxide into another substance. Therefore, it cannot be used directly if one wants to use carbon in the form of carbon dioxide.

3.1.1. Physical adsorption

Adsorption is the process of fixing carbon onto the surface of adsorbents. Physical adsorption, or “physiosorption” is adsorption achieved through physical reactions. The porous structure in zeolites, hydrotalcite, and activated carbons makes all of them currently ideal adsorbents for capturing carbon dioxide. This kind of process is easy to understand and materials are not difficult to find. Physical adsorption can also be carried out in various scopes, giving it the flexibility to be used by most site of CO₂ emission. The pressure and temperature which these adsorbents can normally function are clearly listed.

From the data, conclusion can be drawn that indeed a lot of materials are available for physical adsorption, but every adsorbent has their own drawbacks. All adsorbents are either dependent on high operating pressure, high operating temperature, or low carbon capture capacity. This means that if used on a large scale, industries and companies need to cost a lot in order to start the capture process by high pressure or temperature. The corresponding adsorbents include NaKA, CNT at (Cu₃(btc)₂, MOF-177, Pd-GNP nanocomposite. They demand a range of air pressure from 1111Pa to 4545 kPa and an operating temperature of 373K for NaKA, which is costly to achieve in companies. Notably, MOF-177 has the highest operating pressure, but its significantly harsh terms come with the highest capture capacity of 33.5 mol CO₂/kg Sorbent [9]. There are some adsorbents with operating conditions near room temperature and pressure, yet their capacity is low. Substances like activated carbon, NiO-ACs, and Na-Y, despite their normal operating condition, have low capture capacity of no larger than 10mol CO₂/kg Sorbent. In fact, the highest capacity among these materials are 4.9mol CO₂/kg Sorbent, which is considered low for large scale industries. Industries that produce large amount of CO₂ emission such as those burning fossil fuels for generating electricity might find these materials still costly and, even worse, inconvenient to set up because materials need to bulk together to successfully adsorb all the carbon dioxide emitted. The high cost and inconvenience gave little incentives of setting up these adsorbents to reduce CO₂ emission.

3.1.2. Physical absorption

Absorption, which differs from adsorption by only one letter, is actually similar to the adsorption process. However, absorption takes in the entire CO₂ emission, where adsorption adheres carbon onto the adsorbent’s surface. The main mechanism of physical absorption is the Henry’s law of equilibrium in vapor-liquid mixtures. It asserts that the amount of a gaseous phase dissolved in a unit volume of the solvent is directly proportional to the relative gas pressure in equilibrium with the solvent at any given temperature. Just like adsorption, absorption process requires an absorbent. Rath and others’ research on carbon dioxide separation techniques stated a variety of absorbent: DME of PEG, glycol carbonate, glycol, methanol, and fluorinated solvent. The advantages and disadvantages are also listed. Physical absorption require low energy for regeneration of absorbents, the processes involved also have lower toxicity, lower corrosiveness, and lower vapor pressure which are environmentally-friendly when the absorption is in-process. However, the absorption process is temperature and pressure dependent, which could potentially lead to high operation cost for activating the absorption process. Apart from the cost of operation, degradation of absorbents is causing environmental damage despite its absorbing process of not harming the environment [10].

3.1.3. Membrane-based separation

Membrane-based separation utilizes the semipermeable feature of membranes. Carbon dioxide pass through membranes while other useful gases stay outside due to gas-membrane interactions or kinetic diameter. Membrane-based separation is formed by three steps. Firstly, gas molecules dissolve or are absorbed through the membrane at the side with higher pressure material side. Secondly, the absorbed gas diffuse after entering the membrane to the other side. Thirdly, the absorbed gas desorbs at the low-pressure material side. The main driving force of this method is the pressure difference between two contacting phases on two side of the membrane. Membrane and the absorbents can also be composed of many materials. PVDF, poly propane (PP), PEI, PEI-fSiO₂, and PEEK are all available membrane materials. Absorbents include DI water, NaOH, potassium glycinate, sodium taurinate, activated K₂CO₃, and DEA.

It is notable that the gas molecule passing through the membrane are not always purely carbon dioxide. CH₄, N₂ and even air can also enter the other side of the membrane with carbon dioxide. This affects the efficiency of separation process as not all gas absorbed are carbon dioxide, and some of the membrane that could be used for separating carbon dioxide are filtering other gas molecules. However, if the initial content of gas passing alongside the membrane does not contain corresponding undesired gas, the efficiency might still be unaffected. Therefore, the choice of membrane material and absorbent is crucial if one wants to maximize separating efficiency. Membrane material PEEK in the data table showed an extremely low operating temperature of 37-57K in both absorbent activated K₂CO₃ and DEA, yet it showed high percentage of removal. The trade-off between extreme condition and high removal percentage needs to be evaluated by industries. If initial process of producing carbon dioxide and target product occurs at a low temperature, maybe this material is more ideal because it can operate at a lower temperature which avoids the cost of rising up temperature of product to normal temperature to absorb carbon dioxide.

3.1.4. Hydrate-based separation

Hydrate-based carbon dioxide separation technique uses gas hydrates, which are ice-like, crystalline structures where water molecules form cages that trap gas molecules, including carbon dioxide. Its core mechanism is carbon dioxide's property of forming hydrates more readily than other gases, such as nitrogen or hydrogen. When a gas mixture is exposed to water under certain conditions, like high pressure or low temperature, carbon dioxide molecules will be absorbed into hydrate cages. Crystals containing carbon dioxide can then be removed and stored for further utilization. When the crystal experience increasing temperature or decreasing pressure, the carbon dioxide inside it is released, and the water can be recycled.

This method has high efficiency of capturing carbon dioxide, having its purity up to 99% while captured. Using water as the main material in process and recycling it after releasing carbon dioxide are also accountable for its environmentally-friendly feature apart from previous methods including chemical absorbents. However, enabling hydrates to capture carbon dioxide requires low temperature and high pressure environments to "press" carbon dioxide into the hydrates and let it remain inside. As a result, the economic cost of this method will not be low. Furthermore, this process is found to be slow. There have been attempts to increase the formation rate of hydrates by adding catalysts and promoters like tetrahydrofuran, yet additional chemicals add to the economic cost and raised concerns about environmental damage.

3.1.5. Cryogenic distillation

The cryogenic distillation process separates carbon dioxide from other gases using differences in their boiling points at extremely low temperatures and high pressures. The process of it includes a multi-step sequence. The flue gas is first compressed. Dehydration is also crucial to prevent water and carbon dioxide from freezing and blocking equipment. The gas is then cooled to very low temperatures, for example, between -100°C and -135°C . In these conditions, carbon dioxide deposits into solid or condenses into a liquid, depending on the specific pressure and temperature applied. After that, the solid or liquid carbon dioxide is separated from the remaining non-condensable gases (like nitrogen). The captured carbon dioxide is ultimately recovered as a high-purity liquid or solid stream. In some processes, solid carbon dioxide is further compressed to high pressures (100-200 atm) [11].

This method is simple, only involving a few compressing and condensing process, then the carbon dioxide can be separated. Thus, once set, it could be easily conducted without professionals. It also achieves a high purity of carbon dioxide extracted at 99.9% and has a high recovery rate of 90-95%. Moreover, it does not require chemicals in the entire process, just like hydrate-based separation. Therefore, it cause little environmental damage. On the other hand, the primary drawback is its intense energy consumption. Operating the refrigeration units required for extreme cooling is very expensive, costing 600–660 kWh per ton of carbon dioxide captured. The energy cost makes it not so economically viable to small-scale industries, only suitable for large-scale ones like oil industry which emit a high concentration of carbon dioxide. The pre-treatment stage needs to be dehydrated thoroughly to avoid ice formation when the flue gas contains water. Ice forming inside of the system both slow down the process and adds cost of the amendments on the equipments.

3.2. Chemical separation methods

Chemical separation methods include chemical absorption and chemical looping. These process utilize the chemical property of carbon dioxide to capture it and convert it into other forms. Because carbon is stored as another form, it has lower risk of leakage, but are more difficult to extract for utilization. However, if the “other materials” that these methods convert carbon into are more ideal to use than carbon dioxide, these methods may be more efficient than physical methods.

3.2.1. Chemical absorption

The chemical absorption process captures carbon dioxide by reacting it with a liquid solvent, forming a weak chemical compound. In the chemical absorption, the flue gas containing emitted CO_2 is introduced into the bottom of an absorber column. It flows upward, oppositely-positioned to a "lean" solvent (typically an aqueous amine solution like 15-40% Monoethanolamine - MEA) which is descending. A chemical reaction occurs, binding carbon dioxide to the solvent. The cleaned flue gas exits the top of the column, and the solvent, now containing carbon dioxide, leaves at the bottom. The solvent is then pumped to a stripper (or desorber) column. Here, it is heated to a high temperature in a reboiler, which breaks the chemical bonds and releases nearly pure carbon dioxide. The regenerated "lean" solvent is then cooled and pumped back to the absorber to begin the cycle again.

Chemical absorption is the most developed and mature way of capturing carbon dioxide, so it is easily applicable to a variety of industries. It is also particularly effective for post-combustion

capture from sources like power plants because it can efficiently capture carbon dioxide even when its partial pressure in the flue gas is low. Despite its clear advantage, there are also setbacks of this method. The thermal energy required for solvent regeneration in the reboiler is the process's greatest drawback. This step consumes a significant amount of energy, accounting for ~57.5% of the total energy consumption and 50% of the operating cost, data suggested in Peu et al.'s research. Integrating this system into a power plant also increases electricity costs by 70-80% and reduces the net plant efficiency by 25-30%[11]. Furthermore, Solvents like MEA are susceptible to degradation when exposed to impurities (oxygen, SO₂, etc.) in the flue gas, leading to solvent loss and increased operational costs. Degradation can cause an ~10% increase in operating costs. Implied by Peu et al., amine-based solvents can also be corrosive to equipment, necessitating additional maintenance and corrosion-resistant materials which leads to further cost for amendment in the future.

3.2.2. Chemical looping

Chemical Looping CO₂ Capture and In-Situ Conversion (CL-ICCC) is an integrated process that combines the separation of carbon dioxide from industrial flue gas with its immediate conversion into value-added products, all within a single, cyclic system using a bifunctional material. The process typically operates in two main reactors. In the capture reactor, the industrial flue gas, containing carbon dioxide and other impurities such as oxygen or sulfur dioxide is introduced. Carbon dioxide molecules is chemically adsorbed onto the sorbent component (often an alkali or alkaline earth metal) of the bifunctional material. Therefore, the flue gas is left without carbon dioxide. In the conversion reactor, a reduction agent (for example, hydrogen or methane) is introduced. The captured carbon dioxide is spilled over from the sorption site to the catalytic site (often a metal like Ni, Ru, Fe) on the same material particle, where it is catalytically converted into products like syngas (H₂ + CO), methane (CH₄), or carbon monoxide (CO).

The main difference between chemical looping and chemical absorption is the “loop”. It occurs in the conversion reactor. When carbon dioxide is converted into other products containing carbon, the absorbent used previously to absorb carbon dioxide is simultaneously regenerated and can again be used in the capture reactor. Therefore, the recyclable nature of this method is very economically viable and environmentally-friendly, as it does not require replenishment in ideal circumstances. The operation cost for an ethylene plant integration was 138% lower with ICL-ICCC than with ISCCU [12] proved this point. However, the performance of this method is highly sensitive to flue gas composition. Oxygen impurity oxidizes catalytic metals (e.g., Ni to NiO), hindering reduction and conversion kinetics. Water can compete with CO₂ for adsorption sites and cause catalyst sintering.

3.3. Biological separation methods

Biological separation methods mainly involve microorganism activities of decomposing. It can be further categorized into photosynthetic and non-photosynthetic methods. Just like chemical methods, they convert carbon in carbon dioxide into another form.

3.3.1. Photosynthetic method

This method utilizes photosynthetic organisms, primarily microalgae and cyanobacteria, which consume CO₂ and water in the presence of sunlight to produce organic compounds (biomass) through photosynthesis. The general reaction consumes carbon dioxide and water, through the aid of sunlight, oxygen and nutrient for plant growth is generated. The process involves cultivating these

organisms in open ponds or photobioreactors. CO₂-rich gas (e.g., industrial flue gas) is bubbled through the cultivation system, where the microorganisms absorb and fix the CO₂ directly into their cellular material. These systems can tolerate low CO₂ concentrations and impurities like nitrogen oxides and sulfur oxides often present in industrial flue gas, potentially eliminating the need for extensive pre-cleaning. Additionally, the resulting biomass is not just a waste; it can be fixed with a price by using it as biofuels, animal feed (due to its high protein content), and other bioproducts, promoting economic development. Moreover, this process is powered by solar energy and consumes CO₂, causing no pollution due to biological processes for CO₂ capture. Nevertheless, disadvantage of this method is also very clear. Cultivation is a "land-and-water-intensive process" requiring large surface areas for sunlight exposure. This makes it inapplicable in small-scale usage of CCUS. To make things worse, compared to industrial chemical processes, photosynthetic organisms grow slowly, which can limit the rate of CO₂ capture and volumetric productivity. Additionally, the efficiency of this process is highly dependent on and sensitive to nutrient availability, temperature, pH, and light conditions during cultivation. If cultivation is not successful, the organisms might not achieve ideal efficiency and the whole capturing process will not function normally.

3.3.2. Non-photosynthetic method

This method uses biological systems that do not rely on light energy to fix carbon dioxide. It typically employs engineered microorganisms, such as bacteria and yeast, in bioreactors. These organisms are often metabolically engineered to consume carbon dioxide and a reduced feedstock (such as sugars, syngas, or formate) to produce target molecules like biofuels, chemicals, or biomass in the absence of light. In the research of Rath et al., there is a specific advanced material mentioned: the biogenetically catalyzed GO/MILM membrane, which exhibits very-high selectivity and permeability for carbon dioxide separation due to its moderate viscosity.

Non-photosynthetic processes can achieve very "high yields of biomass" as they are not limited by the efficiency of sunlight capture. Specially engineered genes enable them to absorb carbon dioxide regardless of sunlight, which gives it a higher efficiency of capturing than photosynthetic methods. The use of engineered genes also mean that this method has a high adaptability of different conditions and environments, as long as the microorganisms can survive, they can absorb carbon dioxide. This makes the method applicable in most area needing carbon capture technology. Using organisms rather than chemicals, again, ensures the sustainability like the photosynthetic method, yet implementing this method needs caution of leaking engineered organisms into the wild, which will affect local ecosystems as engineered organisms show higher ability to survive and can be invasive species to local organisms. Another setback will be the complexity of engineering genes. This requires professionals in the biology field, which inevitably increases the cost of buying or developing ideal microorganisms for different industries.

4. Future expectations for carbon dioxide capture and storage

There have already been several methods of capturing carbon through different mechanism in different fields. Nevertheless, current research mainly focus on the absorption capacity, recovery rate, and economic cost of the methods. Another factor is not always tested when researchers explore their target methods, that is the speed of absorption. Therefore, future exploration in this field can target on examining the speed of different methods, using different materials, and lowering the cost of implementing such methods. It is crucial to keep in mind that in terms of industrial production, not only the effectiveness of methods are considered, but corresponding cost of

implementation, and speed of absorption are also taken into account. Moreover, apart from the current materials available for using, new materials of better capacity, higher efficiency, and lower production cost is needed.

5. Conclusion

This study systematically reviews current Carbon Capture, Utilization, and Storage (CCUS) technologies, revealing that no single method offers a universally optimal solution. Physical approaches provide operational simplicity but face challenges in energy consumption and cost at scale. Chemical methods, though efficient, are hindered by high energy penalties and material degradation issues. Biological pathways offer sustainability benefits but remain constrained by slow kinetics and sensitivity to environmental conditions. Therefore, the applicability of each technology is highly context-dependent, influenced by flue gas composition, economic factors, and regional infrastructure.

This research contributes to the field by providing a comparative framework for evaluating CCUS technologies across multiple criteria—including efficiency, cost, and scalability—thereby addressing the need for integrated assessments that support technology selection and policy development. The findings highlight critical research gaps, particularly in material innovation, process integration, and systemic energy optimization. By outlining these priorities, this study aids researchers, engineers, and policymakers in focusing future efforts on developing more efficient, scalable, and economically viable CCUS systems. Ultimately, this work supports global decarbonization goals by facilitating the transition toward a sustainable, low-carbon energy future.

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