

# Physical and Chemical Methods for Mitigating Carbon Dioxide

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**Abstract.** The greenhouse effect caused by greenhouse gases, especially carbon dioxide emissions, has become a central issue in global environmental governance. Traditional emission reduction strategies, although effective, are difficult to meet global climate goals. In response, the scientific community has begun to explore new technologies for capturing, separating, storing and utilizing carbon dioxide through physical and chemical means. These technologies offer potential avenues for greenhouse gas (GHG) management, but still face technical, economic, and environmental challenges before large-scale application. This study systematically evaluates the progress of the application of these physical and chemical means in carbon dioxide (CO<sub>2</sub>) treatment, and discusses in depth the technical bottlenecks and future improvement directions by analyzing the advantages and disadvantages of each technology. It is hoped that this study provides a valuable theoretical basis and practical reference for the development and application of future large-scale CO<sub>2</sub> abatement technologies.

## 1 Introduction

With the increasing global climate change [1], greenhouse gas emissions, especially CO<sub>2</sub> emissions, have become the core issue of global environmental governance. CO<sub>2</sub> is the main factor leading to the greenhouse effect. The continuous rise of CO<sub>2</sub> concentration has a profound impact on the earth's climate system, resulting in a series of serious consequences [2]. Therefore, how to effectively slow down CO<sub>2</sub> emissions, or even remove them from the atmosphere, has become the focus of academia, industry and government policymakers.

Traditional CO<sub>2</sub> emission reduction strategies mainly focus on energy structure adjustment and improving energy efficiency. However, these methods have effectively reduced CO<sub>2</sub> emissions to a certain extent, more is needed to meet the global climate goals. To this end, in recent years, the scientific community has begun to explore a more direct and technical solution, namely the use of chemical and physical means of CO<sub>2</sub> capture, separation, storage and utilisation. These technologies offer a potential pathway to greenhouse gas governance by capturing CO<sub>2</sub> from point sources or the air and converting it into valuable chemicals or long-term storage in geological formations.\*

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Although chemical and physical methods show great promise in the laboratory and small-scale applications, there are technical, economic, and environmental challenges before they can be adopted on a large scale. At present, most of the research focuses on the development of a single technology, and there needs to be more systematic evaluation of multi-technology integration and its practical application potential. In addition, the energy efficiency, stability and economy of CO<sub>2</sub> treatment technology need to be further optimised, and the solution to these problems is crucial to achieving large-scale CO<sub>2</sub> emission reduction in the future.

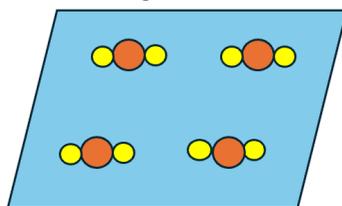
This study systematically evaluates the current progress in the application of physical and chemical methods in CO<sub>2</sub> treatment, and analyse its technical bottlenecks and potential directions for improvement. By combining physical and chemical methods, this paper attempts to provide theoretical support and a practical path for large-scale CO<sub>2</sub> emission reduction in the future. Through this research, we can promote the practical application of physical and chemical methods in coping with climate change and contribute new ideas and technical support to achieving global Sustainable development goals.

## 2 Physical method

Physical methods are a significantly important part of people's usual deal with CO<sub>2</sub>. Common physical methods of CO<sub>2</sub> include physical adsorption, membrane separation, and cryogenic condensation. These methods exploit the physical properties of CO<sub>2</sub> to achieve its capture and separation through different mechanisms. The following is a detailed description of each method.

### 2.1 Physical adsorption

Among CO<sub>2</sub> capture technologies, adsorption has garnered significant attention due to its advantageous characteristics revealed in recent years. Physical adsorption is a process where gas molecules are adsorbed into the surface of solid materials through physical forces such as van der Waals forces and electrostatic attraction. This process involves weak intermolecular interactions without forming or breaking chemical bonds. Porous carbon-based materials have become one of the most versatile CO<sub>2</sub> adsorbents [3]. Porous carbon-based materials are a class of adsorbents characterised by their high surface area, tunable pore structures, and excellent adsorption properties. These materials include activated carbon, carbon nanotubes, and graphene. They can effectively capture and store CO<sub>2</sub> because of their high porosity and surface reactivity. The process of physisorption (CO<sub>2</sub> adheres to the adsorbent without reacting) is shown in Figure 1.



**Fig. 1.** Schematic diagram of CO<sub>2</sub> physical adsorption process [4].

### 2.2 Membrane separation

Membrane separation is a process that utilises selectively permeable membranes to separate components of a gas mixture based on their different permeation rates. This method is becoming more and more popular for capturing CO<sub>2</sub> because it is environmentally friendly,

highly efficient and energy-saving. CO<sub>2</sub> molecules have the capability to penetrate more easily in specific membrane materials due to their lower molecular size and higher solubility. Membrane separation is divided into 5 categories: Polymeric membrane separation, inorganic membrane separation, mixed matrix membrane separation, composite membrane separation and liquid membrane separation. As a membrane in liquid Membrane Separation, the Water membrane can quickly and effectively absorb CO<sub>2</sub> [5]. What is more, water can not only be easily gotten but also be more stable than other membranes and eco-friendly. CO<sub>2</sub> membrane separation technology is important promoting clean energy production.

### 2.3 Cryogenic condensation

The cryogenic condensation method is a technology that condenses CO<sub>2</sub> from gas to liquid by reducing the temperature so as to achieve gas separation and capture. When the temperature of CO<sub>2</sub> gas is lowered below its condensation point, the CO<sub>2</sub> gas molecules condense into a liquid state, which can be separated from the gas mixture. Because CO<sub>2</sub> has a relatively high condensation point, condensing and separating at lower temperatures is easy. Using this principle, CO<sub>2</sub> can be extracted from a variety of mixed gases. On the one hand, it can be used in commercial, industrial, medical, and other fields, such as carbonated beverages, dry ice, and other uses. Moreover, it can reduce CO<sub>2</sub> in the atmosphere and reduce the greenhouse effect.

## 3 Chemical method

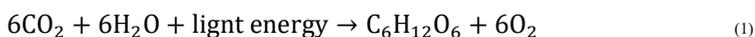
Chemical methods play a vital role in reducing CO<sub>2</sub>. These methods are not only efficient and applicable, but also convert CO<sub>2</sub> into valuable products, driving resource recycling and sustainable development. On a global scale, using chemical methods to capture, fix, and convert CO<sub>2</sub> has become an important strategy to combat climate change and the greenhouse effect. The following will discuss several major chemical methods, including biochemical methods, solvent absorption, carbonation reaction, and catalytic conversion, and analyze their principles, applications, advantages, and challenges.

### 3.1 Physical adsorption

Biochemical Methods use microorganisms or enzymes to catalyze the fixation and conversion of CO<sub>2</sub> to convert CO<sub>2</sub> into valuable chemicals or biomass through biochemical reactions. These methods rely primarily on the ability of organisms to fix and transform CO<sub>2</sub> in natural processes. Biochemical methods are mainly divided into two methods: photosynthetic organisms and microbial electrochemical systems.

#### 3.1.1 Photosynthetic organisms

Photosynthetic organisms fix CO<sub>2</sub> through photosynthesis. The main process of photosynthesis is (Eq.1):



Photosynthesis is divided into two stages: the light reaction and the dark reaction. In the light reaction, light is absorbed by chlorophyll and converted into chemical energy. In the dark reaction, CO<sub>2</sub> is fixed and converted into glucose through a series of reactions. According to this principle, CO<sub>2</sub> can be effectively converted into glucose and oxygen, which

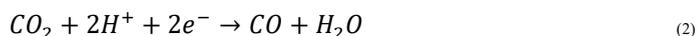
not only reduces CO<sub>2</sub> in the atmosphere, but also makes it a more useful substance. After learning the principle of photosynthetic organisms, here are two practical parts of that principle.

First, biological sequestration of CO<sub>2</sub> is used. Algae's high growth rate and ability to adapt to a variety of environments make them ideal for bioenergy production and atmospheric CO<sub>2</sub> emission reduction. Microalgae are highly efficient in solar energy conversion and biomass production. Certain species exhibit high CO<sub>2</sub> fixation rates, making them very effective at reducing atmospheric CO<sub>2</sub> concentrations. These microorganisms can trap carbon from the atmosphere and flue gas. The fixed CO<sub>2</sub> is converted into biomass and can be used for a variety of purposes, including biofuel production. The efficiency of microalgae in photosynthesis ensures that a large amount of CO<sub>2</sub> is removed from the atmosphere. What is more, seaweed or Marine macroalgae also play an important role in CO<sub>2</sub> sequestration. They participate in the carbon cycle by converting CO<sub>2</sub> into organic matter through photosynthesis. Schemes like the Ocean Macroalgae Afforestation (OMA) aim to use seaweed farming to offset man-made CO<sub>2</sub> emissions. Seaweed farming in coastal areas enhances CO<sub>2</sub> capture. This process involves the growth of seaweed, which absorbs CO<sub>2</sub> and thus reduces the CO<sub>2</sub> concentration in the atmosphere. The harvested seaweed biomass can be further processed into biofuels, and the resulting biomass can be used for bioenergy, providing a sustainable way to manage carbon and thus achieve negative carbon emissions [6].

Second, Microalgae bioreactors can be used. An algal bioreactor is a device for cultivating microalgae on a large scale, using the photosynthesis of microalgae to fix and convert CO<sub>2</sub>. These reactors maximize the biomass yield and CO<sub>2</sub> capture efficiency of microalgae by optimizing growth conditions such as light, temperature, and nutrient supply [7].

### 3.1.2 Microbial electrochemical systems

Microbial Electrochemical Systems (MES) use electroactive microorganisms to catalyze the reduction of CO<sub>2</sub> on electrodes [8]. Electrons can be transferred from the electrode to CO<sub>2</sub> through the metabolic activity of these specific microbes, facilitating their conversion into valuable chemicals such as formic acid, carbon monoxide, or acetic acid. The key reactions typically include:



Or



The electrons and protons produced by the anode microorganisms oxidize the organic substrate, and the electrons are transmitted to the cathode through an external circuit, where they are combined with CO<sub>2</sub> under the action of electroactive microorganisms to achieve efficient CO<sub>2</sub> reduction. MES can not only effectively reduce greenhouse gas emissions, but also capture and reduce CO<sub>2</sub> while treating organic wastewater, which has significant environmental and economic benefits. The system, combined with renewable energy, provides a low energy consumption and efficient CO<sub>2</sub> reduction solution. However, further research is needed regarding microbial activity optimization, electrode material durability, and large-scale applications.

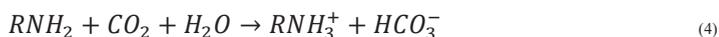
### 3.2 Solvent adsorption

The solvent absorption method has been widely studied and applied due to its mature and efficient CO<sub>2</sub> trapping technology. The solvent absorption method is a chemical reaction

between chemical solvents and CO<sub>2</sub>: the CO<sub>2</sub> in the gas is absorbed and fixed, and then the pure CO<sub>2</sub> is released through the regeneration process. The method uses the chemical properties of the solvent to form reversible compounds with CO<sub>2</sub> under specific conditions, thereby achieving the capture and release of CO<sub>2</sub>. The following is the basic principle and process of solvent absorption.

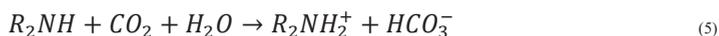
Solvent absorption primarily relies on the chemical reaction between the solvent and CO<sub>2</sub>. The most common solvents are amine-based solvents, such as monoethanolamine (MEA), diethanolamine (DEA), and methyldiethanolamine (MDEA) [9]. These amine-based solvents react with CO<sub>2</sub> through the following reactions:

MEA and CO<sub>2</sub> reaction:



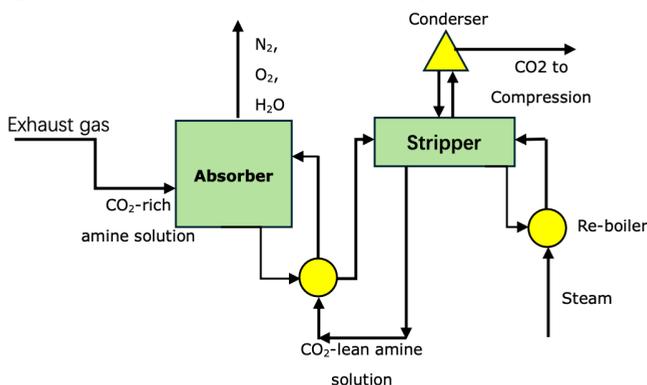
Where R stands for hydroxyethyl

DEA and CO<sub>2</sub> reaction:



These reactions produce bicarbonate (HCO<sub>3</sub><sup>-</sup>) and amine salts (RNH<sub>3</sub><sup>+</sup>). During the regeneration process, these reactions are reversible. By heating or reducing the pressure, the absorbed CO<sub>2</sub> can be released, and the solvent is regenerated.

A schematic diagram of an absorber/stripper system for separating carbon dioxide from exhaust gases is shown in Figure 2. The absorption process usually takes place in an absorption tower. Gas containing CO<sub>2</sub> enters from the bottom of the absorption tower and comes into countercurrent contact with the solvent sprayed down from the top. In this process, CO<sub>2</sub> is absorbed by the solvent, and a chemical reaction occurs. The process can be divided into the following steps: First, the gas enters the absorption tower. The exhaust gas containing a high concentration of CO<sub>2</sub> is introduced from the bottom of the absorption tower and is in contact with the solvent through the packing layer or plate tower. The second step is a solvent spray. Absorb the spray solvent at the top of the tower, make it flow down the tower wall, and countercurrent contact with the rising gas. The solvent can be an amine solvent (MEA, DEA, or MDEA) or other solvents with absorptive capacity. Then, there is the absorption reaction. CO<sub>2</sub> molecules react chemically with solvent molecules at the gas-liquid interface to form stable compounds such as bicarbonate and amine salt. Finally, the purification gas is discharged. The purified gas is discharged from the top of the absorption tower, and the CO<sub>2</sub> concentration is significantly reduced to achieve CO<sub>2</sub> capture and reduction.



**Fig. 2.** Simplified PFD of an absorber/stripper system for CO<sub>2</sub> separation from exhaust gas [10].

The solvent absorption method has several advantages over other CO<sub>2</sub> capture technologies. First, the absorption efficiency of the solvent absorption method is high, and a large amount of CO<sub>2</sub> can be captured, especially for high-concentration CO<sub>2</sub> emission sources. Secondly, the method has good selectivity and can effectively distinguish and preferentially absorb CO<sub>2</sub> without interference from other gases. In addition, the solvent absorption technology is mature, proven by years of industrial practice, with reliable operating performance and controllable operating parameters. Therefore, the solvent absorption method is widely used in large industrial facilities such as power plants and chemical plants and has become one of the key technologies for CO<sub>2</sub> emission reduction.

### 3.3 Carbonation reaction

Carbonation reaction, as an emerging CO<sub>2</sub> capture and fixation technology, is a process that converts CO<sub>2</sub> into stable carbonates by using the chemical reaction between CO<sub>2</sub> and alkaline minerals or industrial wastes. This process not only enables the permanent fixation of CO<sub>2</sub>, but also converts industrial by-products into valuable materials. The following is the basic principle of carbonation reaction.

The carbonation reaction consists of three basic steps:

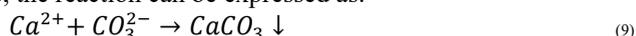
The first step is the dissolution of CO<sub>2</sub>: in the presence of water, CO<sub>2</sub> is first dissolved in water to form carbonic acid (H<sub>2</sub>CO<sub>3</sub>). This process can be expressed as:



The second step is the dissociation of carbonic acid: Carbonic acid dissociates in an aqueous solution into hydrogen ions (H<sup>+</sup>) and bicarbonate ions (HCO<sub>3</sub><sup>-</sup>), and further dissociates into hydrogen ions and carbonate ions (CO<sub>3</sub><sup>2-</sup>). These dissociation reactions can be expressed as:



The third is the precipitation of carbonate ions: the reaction of carbonate ions with metal cations (e.g. Ca<sup>2+</sup>, Mg<sup>2+</sup>) produces an insoluble carbonate precipitate. Taking the formation of calcium carbonate as an example, the reaction can be expressed as:



CO<sub>2</sub> reacts directly with metal oxides to form carbonates in an anhydrous environment. This direct reaction usually occurs at higher temperatures and sometimes requires a catalyst to increase the reaction rate. Taking magnesium oxide (MgO) as an example, the reaction is as follows:



The energy change in this reaction is negative (i.e., exothermic) because the carbonate formation is thermodynamically stable. This means that the resulting carbonate is difficult to reverse back into CO<sub>2</sub> and metal oxides under natural conditions so that the CO<sub>2</sub> can be fixed for a long time [11].

The common carbonation is mineral carbonation. Mineral carbonation is a process in which CO<sub>2</sub> reacts with minerals containing metal ions such as magnesium and calcium (such as serpentine and olivine) to form stable carbonates. This process is an exothermic reaction and can occur naturally or through accelerated reactions in industrial Settings. Mineral carbonation is a long-term form of CO<sub>2</sub> sequestration because the resulting carbonate is very

stable under environmental conditions and does not decompose easily, which can effectively fix CO<sub>2</sub> and prevent it from re-entering the atmosphere. This method can not only utilize the abundant mineral resources in nature but also achieve the permanent storage of CO<sub>2</sub> by treating industrial by-products. Mineral carbonation technology is considered one of the safest and most feasible methods of carbon dioxide capture and storage and is particularly suitable for implementation in areas rich in these minerals, such as the northern regions of Pakistan [12].

### 3.4 Catalytic conversion

Catalytic Conversion refers to the process of using catalysts to accelerate chemical reactions. A catalyst is a substance that increases the rate of a chemical reaction without being consumed by itself. In the catalytic conversion process, the catalyst enables the reactant to be converted to the target product more quickly and efficiently by reducing the activation energy of the reaction [13]. The principle of catalytic conversion in the treatment of CO<sub>2</sub> mainly involves accelerating a chemical reaction through a catalyst, thereby efficiently converting CO<sub>2</sub> into other chemicals or fuels. Here are the main principles:

#### 3.4.1 Catalytic hydrogenation reaction

In catalytic hydrogenation reactions, the catalyst is usually a metal (such as nickel, copper, iron [14], etc.) whose role is to reduce the activation energy of the reaction, causing CO<sub>2</sub> to react with hydrogen (H<sub>2</sub>) to form chemicals such as methane (CH<sub>4</sub>) and methanol (CH<sub>3</sub>OH). The reaction formula is as follows:



These reactions are usually carried out under high temperature and pressure conditions, and the catalyst can increase the reaction rate and the product's selectivity.

#### 3.4.2 Photocatalytic reduction reaction

Photocatalytic reduction uses a semiconductor material (such as titanium dioxide TiO<sub>2</sub> [15]) as a catalyst to excite electrons to jump from the valence band to the conduction band under light, forming an electron-hole pair. Electrons can reduce CO<sub>2</sub> to form carbon monoxide (CO) or methanol (CH<sub>3</sub>), while holes are decomposed by water to produce O<sub>2</sub>. The reaction process can be simplified as:



#### 3.4.3 Dry Reforming of Methane (DRM)

In the DRM process, CO<sub>2</sub> and CH<sub>4</sub> react in the presence of a catalyst to produce syngas, a mixture of H<sub>2</sub> and CO [16]. The chemical reaction can be represented as:



Syngas can be further used to produce liquid fuels, chemicals, and other energy products. This process not only converts greenhouse gases, but also provides raw materials for industrial production.

## 4 Conclusions

This study reveals the advantages and shortcomings of physical and chemical means in CO<sub>2</sub> treatment by systematically evaluating the application of these technologies. Physical methods such as physical adsorption, membrane separation and low-temperature condensation show good application prospects and are suitable for CO<sub>2</sub> capture and separation, while chemical methods such as biochemical methods, solvent absorption, carbonation reactions and catalytic conversion can convert CO<sub>2</sub> into valuable products, thus promoting resource recycling. Although these technologies have shown great potential in laboratory and small-scale applications, they still need to be further optimized in terms of energy efficiency, stability and economics. Future research should focus on the systematic assessment and practical application potential of multi-technology integration in order to realize large-scale CO<sub>2</sub> emission reduction and provide theoretical support and practical pathways for addressing climate change.

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