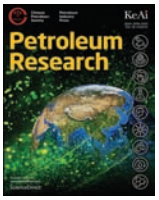
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Review Article

Characteristics, emissions, capture, storage, and utilization of carbon dioxide: A comprehensive review of challenges and technologies for greenhouse gas mitigation

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ABSTRACT

The capture, storage, and utilization of carbon dioxide (CO_2) are pivotal in combating climate change and mitigating greenhouse gas (GHG) emissions. This review offers a comprehensive and critically focused analysis of post-capture CO_2 handling methods, including storage, adsorption, and utilization, with a particular emphasis on emerging and innovative technologies. Distinctively, this study highlights advanced CO_2 conversion pathways—such as photocatalytic and photoelectrochemical reduction, membrane-based separations, and mineralization—by analyzing their mechanisms, energy demands, techno-economic feasibility, and integration potential with renewable energy sources. The review further explores the role of natural systems, especially microalgae and porous materials, in CO_2 biofixation and adsorption under industrial conditions. Unlike conventional reviews, this work provides an in-depth comparative assessment of major capture methods (e.g., cryogenic separation, chemical absorption, and mixed-matrix membranes), emphasizing recent advancements and material innovations that enhance selectivity, thermal stability, and operational efficiency. By integrating perspectives from material science, process engineering, and environmental policy, this review presents a novel synthesis of current challenges and future opportunities in circular carbon management. These insights aim to support the development of scalable, cost-effective, and sustainable CO_2 mitigation strategies for industrial deployment.

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1. Introduction

Carbon dioxide (CO_2) is a naturally occurring greenhouse gas (GHG) that plays a significant role in the Earth's carbon cycle (Dinu et al., 2022; Ghasem, 2023; Jaiswal et al., 2020; Kludze et al., 2022; Manae et al., 2022; Romano et al., 2024; Zanatta, 2023). However, since the Industrial Revolution, anthropogenic activities—especially the combustion of fossil fuels such as coal, oil, and natural gas—have significantly increased atmospheric CO_2 concentrations (Jiang et al., 2024; Ugur et al., 2023; Zhang et al., 2024a). These activities include electricity generation, transportation, industrial processes, and land use changes such as deforestation (Buchheiser et al., 2023; Do and Truong, 2023; Filosa et al., 2023; High et al., 2022; Liu et al., 2024; Su et al., 2022; Yang et al., 2024; Zhang et al., 2022). Additionally, CO_2 is generated through the respiration of animals and humans, during which atmospheric oxygen reacts with carbon from food to form CO_2 (Andrews et al., 2023). Other natural processes, such as the fermentation of organic matter and the weathering of rocks, also contribute to CO_2 production by combining carbon with oxygen (Zhao et al., 2024; Zondervan et al., 2023). Global climate change is recognized as one of the foremost environmental and energy challenges we face today (Anderson and Newell, 2003; Gao et al., 2024). Despite uncertainties surrounding the scientific and economic aspects, it is clear that human activities are impacting the Earth's climate. Consequently, numerous countries have

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collaborated to enhance scientific understanding of global warming, driven by concerns regarding these climatic changes.

Fig. 1 provides a detailed overview of the various processes responsible for the generation and release of CO_2 into the atmosphere (Tan and Nielsen, 2022). It clearly illustrates that the energy sector stands out as the largest contributor to global CO_2 emissions (He et al., 2024). This is primarily due to the combustion of fossil fuels—including coal, oil, and natural gas—for the production of electricity and heat (Ashokan et al., 2024; Schindler et al., 2024; Xie et al., 2023). These fuels release substantial amounts of CO_2 when burned, particularly in power plants and industrial boilers (Wang et al., 2022).Beyond the energy sector, transportation is another major source of CO_2 emissions. This includes emissions from a wide range of vehicles and systems such as automobiles, trucks, ships, and airplanes—all of which rely heavily on gasoline, diesel, or other petroleum-based fuels. These fuels release CO_2 during internal combustion, making the transportation sector one of the top contributors to GHG emissions. Industrial processes, particularly in the manufacturing of materials like steel and iron, also release significant amounts of CO_2. In these industries, coke—a carbon-rich material derived from coal—is used as a reducing agent to convert iron ore into metal, a process that emits large volumes of CO_2. Cement production is another substantial source of CO_2, largely due to a process known as calcination. During calcination, $CaCO_3$ is heated to produce lime CaO, releasing CO_2 as a chemical byproduct. This reaction alone contributes to a notable percentage of global industrial CO_2 emissions.

Furthermore, the chemical and petrochemical industries, which rely on oil and natural gas to produce a wide array of products (e.g., plastics, fertilizers, solvents), generate CO_2 both through the use of energy and as a byproduct of chemical reactions. Lastly, waste management activities, particularly incineration (burning of municipal or industrial waste), also contribute to CO_2 emissions. While these processes can help reduce the volume of waste, they often release CO_2 and other pollutants into the atmosphere. Similarly, certain recycling processes that involve energy-intensive treatment or chemical transformation of materials may emit CO_2, especially if powered by fossil fuel-based energy sources. Together, these sectors form a comprehensive picture of how human activities contribute to the steady rise in atmospheric CO_2 levels, as depicted in Fig. 1.

Human activities, such as the extensive use of fossil fuels for energy generation, population growth, and industrial expansion, have caused a marked increase in CO_2 levels in the Earth's atmosphere (Cavelius et al., 2023; Sorimachi, 2022). This surge can lead to severe consequences, including global warming, climate change, and glacial melting (Jiang et al., 2023). To combat these emissions, it is crucial to adopt clean energy sources, such as solar, wind, and other renewables (Bahgaat, 2023). Furthermore, reducing dependence on fossil fuels and shifting to public transportation and cleaner transport options can also have a significant impact (Soto, 2024).

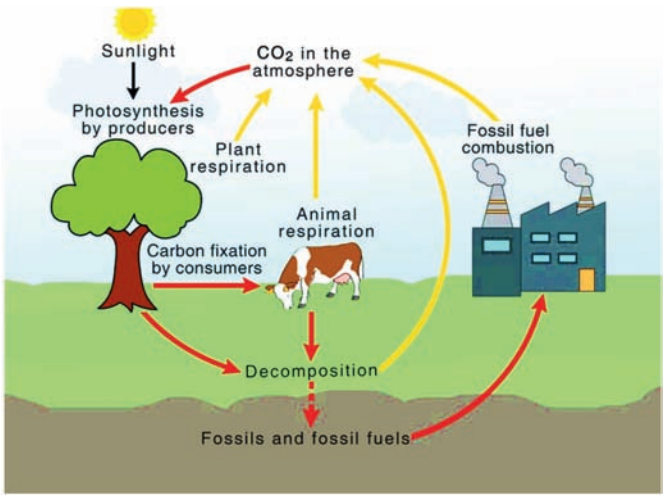


Fig. 1. CO_2 production cycle.

Human activities significantly contribute to the rise of GHG in the atmosphere through fossil fuel combustion, various industrial processes, and changes in land use (Alley et al., 2003; Crowley, 2000; Karl and Trenberth, 2003). These gases trap heat, preventing it from escaping back into space. CO_2 is the most common GHG, accounting for 82% of total GHG emissions in the United States from 1991 to 2000 (Cao et al., 2024; Huang et al., 2023, 2024). Approximately 96% of these carbon emissions stem from the use of fossil fuels for energy (Anser, 2019; Burrington, 2024; Kiehbadroudinezhad et al., 2023; Vogt and Weckhuysen, 2024). Consequently, efforts to address climate change are largely focused on reducing CO_2 emissions.

Historically, power generation and combustion processes have elevated atmospheric CO_2 levels from 325 ppm to 408 ppm, contributing to over 60% of the global temperature increase (Bezyk et al., 2023; Liu et al., 2024; Nocito and Dibenedetto, 2020; Yang et al., 2022). This situation has prompted the scientific community to seek solutions for reducing CO_2 emissions to prevent global temperatures from rising more than 2 °C. Reducing CO_2 emissions is considered a beneficial step, as it helps conserve fossil carbon resources and decreases heat transfer to the atmosphere (Aresta et al., 2019; Goldberg et al., 2023; Maleki et al., 2024).

In 2008, CO_2 emissions from electricity production using fossil fuels accounted for nearly 40% of the total CO_2 emissions in the United States, with projections indicating that this figure could rise to 42% by 2030 (Cheng et al., 2023; Wei, 2024). To reconcile the need for reducing GHG emissions with the demand for a sustainable energy supply, the scientific community, industry, and policymakers have identified carbon capture and storage (CCS) technology as a promising solution (Krogh et al., 2024; Subraveti et al., 2023; Zheng et al., 2023). CCS involves capturing CO_2 from industrial or power generation sources and subsequently injecting it into underground geological formations for long-term storage (Braun, 2017).

Historically, enhancing energy efficiency and replacing fossil fuels with low-carbon energy sources were viewed as the primary strategies for reducing CO_2 emissions (Chukwunonso et al., 2024; Y. Wang et al., 2022; Zhuang et al., 2022). However, in recent decades, the focus has shifted towards the development of CCS technologies, which enable the continued use of fossil fuels (Akbari et al., 2024; Gupta and Gupta, 2023; Sonowal and Saikia, 2022). These technologies capture CO_2 from large, stationary sources, compress it, and transport it to locations such as aquifers, depleted oil fields, or deep ocean sites to prevent its release into the atmosphere. In addition to CO_2, reducing other pollutants such as black carbon, tropospheric ozone (O_3), particulate matter, and nitrogen oxides also helps mitigate climate change and enhances the effectiveness of CCS technology (Hata et al., 2023).

Recent studies have contributed valuable insights into the complex mechanisms involved in CO_2 geological storage. In 2024, Ramadhan et al. explored the role of reservoir geomechanics in tight sandstone formations, demonstrating how mechanical properties influence CO_2 plume migration and enhance storage security through improved residual and solubility trapping. In a related study, the same authors examined how factors such as temperature, hysteresis, permeability anisotropy, and rock compressibility affect the efficiency of structural, residual, and

solubility trapping mechanisms, confirming that optimal reservoir conditions are critical for long-term containment (Ramadhan et al., 2024a,b; Ramadhan et al., 2024a,b). Complementing this perspective, Thanasaksukthawee et al. (2025) investigated geochemical interactions between CO_2-saturated brine and sandstone, revealing that mineral dissolution and precipitation can alter porosity and permeability, albeit with limited impact on large-scale storage capacity. These findings underscore the importance of integrating geomechanical, geochemical, and flow-related factors in CCS site selection and design (Thanasaksukthawee et al., 2025).

In the context of CO_2 capture, Wilson et al. (2025) provided a comprehensive review of technological developments aimed at reducing emissions from industrial flue gases. Their work emphasized that while significant advances have been made in capture techniques, cost remains the most critical barrier to widespread adoption. As the most expensive component of the CCS chain, carbon capture demands innovations in material performance, energy efficiency, and system integration to ensure economic feasibility. Addressing these financial and operational challenges is vital for scaling up CCS and achieving global climate targets. Together, these studies highlight the multidisciplinary nature of carbon capture and storage technologies and the need for holistic strategies that encompass engineering, geoscience, and policy dimensions (Wilson et al., 2025).

Hawez and Asim (2024) conducted research exploring CCS technology as a crucial method for lowering GHG emissions. This technology involves capturing CO_2 from industrial processes and power plants and injecting it underground for long-term storage. They emphasized the effects of regional pressure depletion on CCS projects and the importance of maintaining suitable pressure in storage formations, which can improve the efficiency, safety, and environmental sustainability of these initiatives. Meanwhile, Sen and Mukherjee (2024) highlighted that the rise in global average temperatures due to the ongoing emission of human-made GHGs, especially CO_2, is one of the most significant challenges facing humanity today. To tackle this issue, it is critical to reduce fossil fuel consumption and store atmospheric CO_2. CO_2 reduction strategies include CCS technologies and the use and storage of biological carbon capture and utilization (bio-CCU), with algal bio-CCU in biorefineries being recognized as a more environmentally friendly and economically feasible option. Algal biorefineries can utilize CO_2 to produce third-generation biofuels and valuable products, thereby reducing dependence on fossil fuels and supporting the achievement of the United Nations Sustainable Development Goals (SDGs).

Fig. 2 illustrates the year-over-year growth in the volume of CO_2 being stored, either through underground geological storage, industrial utilization, or other CCS technologies. This upward trend reflects the increasing global attention being directed toward CO_2 management as a critical response to climate change. The steady rise in CO_2 storage indicates that more countries, industries, and research institutions are actively investing in and implementing CO_2 sequestration strategies. The figure emphasizes not only the growing scale of these efforts but also the pressing need to expand and accelerate such initiatives. Given the continuous rise in CO_2 emissions worldwide, storing captured CO_2 has become an urgent environmental priority to mitigate the effects of global warming. Thus, the data in Fig. 2 serve as a visual confirmation of both the importance of CO_2 storage as a climate solution and the momentum that is building in this field on a global scale.

In this paper, a comprehensive and forward-looking review is conducted to consolidate recent advances in CCUS. Beyond presenting detailed information on GHGs and CO_2 emission sources—especially from electricity generation—this study

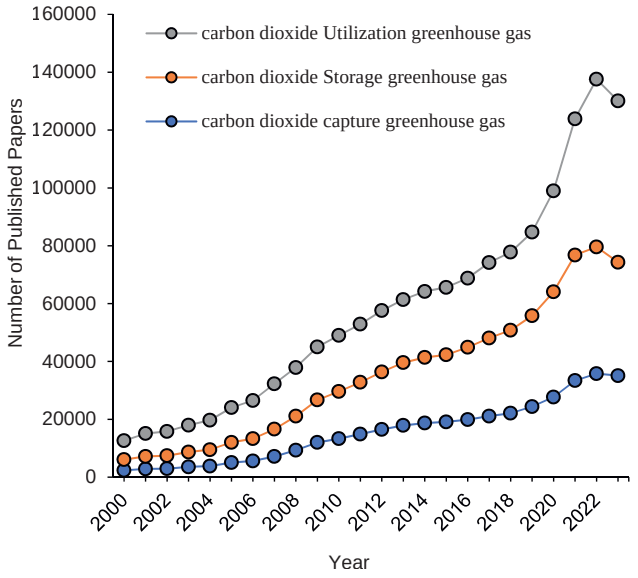


Fig. 2. Number of published articles on carbon capture, storage, and utilization technologies.

distinguishes itself by emphasizing emerging and innovative technologies that are reshaping the future of carbon management. Specifically, novel approaches such as membrane-based separations, cryogenic processing, mineral carbonation, and photocatalytic and photoelectrochemical CO_2 reduction are critically assessed in terms of their mechanism, performance, integration potential, and scalability. The review also introduces a cross-disciplinary framework that bridges engineering fundamentals, material innovations, and sustainability considerations, offering a structured comparison between conventional and next-generation CO_2 mitigation strategies. Unlike traditional overviews, this work highlights the synergies between renewable energy integration and CO_2 valorization pathways, contributing to the advancement of a circular carbon economy. By fostering international perspectives and aligning technological insights with environmental imperatives, this study provides a novel, balanced, and application-oriented contribution to the CCUS research landscape.

2. What is the CO_2?

CO_2 is a colorless, odorless gas composed of carbon and oxygen, produced naturally through processes like combustion, fermentation, and respiration (Labidi et al., 2023; Miroshnichenko et al., 2023). It forms during complete combustion and has a specific gravity higher than air, making it accumulate in lower areas (Chen et al., 2024; Gkotsis et al., 2023; Miyazaki et al., 2023) (see Fig. 3).

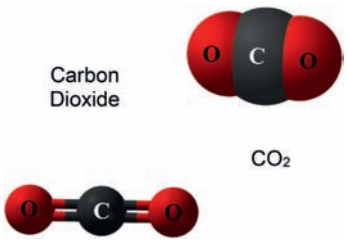


Fig. 3. Covalent structure of the CO_2 molecule.

Although it constitutes only about 0.04% of the Earth's atmosphere, CO_2 plays a crucial role in plant photosynthesis and temperature regulation through the greenhouse effect (de Carvalho Silvello et al., 2022). Its increasing atmospheric concentration due to fossil fuel use has made it a major GHG and environmental concern, as it traps infrared radiation, contributing to global warming (Zhuang et al., 2023). CO_2 also has notable physical and chemical characteristics (He et al., 2022; Rajesh and Ramachandran, 2024). At high concentrations, it can pose health risks such as shortness of breath or suffocation, but it is widely used in fire extinguishers due to its non-combustible nature (Amaral et al., 2021). It occurs naturally from volcanic activity, geysers, and carbonate rock dissolution, and is also present in water bodies (Hemmatifar et al., 2022; Xia et al., 2022).

2.1. Characteristic of CO_2

2.1.1. Structure and bonding of CO_2

As illustrated in Fig. 3, the CO_2 molecule possesses a linear geometry, meaning that its atoms are arranged in a straight line (Barlocco et al., 2023). In this structure, a single carbon atom is positioned at the center, with two oxygen atoms symmetrically placed on either side. This configuration results in a bond angle of exactly 180° between the atoms, confirming its linear shape (Mohamed-Ezzat et al., 2024; Spahr et al., 2021). The bonds between the carbon and each oxygen atom are identical in length, measuring approximately 113.6 pm (pm). This bond length is shorter than that of a typical single carbon–oxygen (C–O) bond, which generally ranges around 143 p.m. The reduced bond length indicates that the C═O bonds in CO_2 are not single but rather double bonds, which are stronger and shorter due to the sharing of two electron pairs between atoms instead of just one. This symmetrical double-bonded structure is a key reason why the CO_2 molecule is nonpolar, despite containing polar bonds. The equal distribution of charge and linear symmetry cause the individual dipoles of each C═O bond to cancel out, resulting in no net dipole moment for the molecule. Overall, the bond characteristics in CO_2 reflect a highly stable and tightly bound molecular structure, which is consistent with its behavior and reactivity in various chemical and environmental processes.

The CO_2 molecule is nonpolar due to its centrosymmetric structure (Zhou et al., 2024). Consequently, the CO_2 molecule exhibits only two detectable vibrational modes in the infrared (IR) spectrum, as there is no change in the electric dipole moment during these modes. Additionally, CO_2 features a symmetric stretching mode at a wavelength of 1388 cm^{-1}, which is exclusively observed in the Raman spectrum. The Raman spectrum functions through the scattering of light, allowing it to identify vibrational modes that are not detectable in the infrared spectrum (Begušić and Blake, 2023; Zhu et al., 2021). This symmetric stretching mode does not appear in the infrared spectrum because there is no change in the electric dipole moment during vibration, making it only observable in the Raman spectrum, which is based on light scattering.

2.1.2. CO_2 in aqueous solution

CO_2 dissolves in water and reacts to form carbonic acid (H_2CO_3), a weak acid. The formation of H_2CO_3 is represented by the reaction $CO_2 + H_2O \leftrightarrow H_2CO_3$ (Dasgupta et al., 2023; Wang et al., 2016). In aqueous solutions, H_2CO_3 partially ionizes in two stages (Lee et al., 2021b). In the first stage, H_2CO_3 ionizes into hydrogen ions (H^+) and bicarbonate ions (HCO_3^-) as described by the equation $H_2CO_3 \leftrightarrow H^+ + HCO_3^-$. In the second stage, bicarbonate ions can further ionize into additional H^+ and carbonate ions CO_3^{2-} as shown by $HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$.

As a result of these ionizations, the aqueous solution of CO_2 comprises a mixture of CO_2, H_2CO_3, HCO_3^-, and CO_3^{2-} (Deng et al., 2023; Lan et al., 2022; Lee et al., 2021a). The chemical equilibria of these reactions are influenced by the pH of the solution and the concentrations of the various ions present (Min et al., 2023; Zhang, 2024). Lower pH values correspond to higher concentrations of H_2CO_3 and dissolved CO_2, while higher pH values favor the presence of bicarbonate and carbonate ions. These equilibria play a crucial role in biological systems and environmental contexts, such as in oceans where the balance between CO_2, H_2CO_3, bicarbonate, and carbonate is essential for regulating water pH and supporting marine life. Furthermore, in biological organisms, the equilibrium involving CO_2 is vital for metabolic processes and maintaining acid-base homeostasis, facilitating gas exchange and pH regulation within the bloodstream (Amador et al., 2023; Li et al., 2023).

2.1.3. Chemical reactions of CO_2

CO_2 is recognized as a weak electrophile and can react with hydroxides and other nucleophiles (LoPachin et al., 2019; Remmerswaal et al., 2024). One significant reaction of CO_2 occurs with water, where water acts as a hydroxide nucleophile, leading to the formation of H_2CO_3. Additionally, other nucleophilic acids can react with CO_2, particularly carbanions, which are transient negative ions (Zhang et al., 2023). In the Grignard reaction, for instance, carbanions attack CO_2 to produce products such as RCO_2M, where R represents an organic group and M denotes a catalyst or another species. This reaction is represented by the equation $MR + CO_2 \rightarrow RCO_2M$.

Furthermore, the reduction of CO_2 to carbon monoxide (CO) is a challenging and slow process, requiring two electrons and two protons, as shown in the equation $CO_2 + 2e^- + 2H^+ \rightarrow CO + H_2O$ (Bondue et al., 2020). This reduction typically occurs under specific conditions and often involves catalysts and suitable methodologies (Yang et al., 2024). Overall, the chemical reactions of CO_2 play a crucial role in various chemical and environmental processes, including the absorption and conversion of GHGs and the production of sustainable fuels (Kang et al., 2023; Saleh, 2022; Wang et al., 2017; Wei et al., 2023).

2.1.4. Physical reactions of CO_2

CO_2 possesses unique physical properties that distinguish it from other gases. It is colorless and odorless at low concentrations but develops a sharp, acidic smell at higher levels (Geng et al., 2023; Mehra and Paul, 2022a, 2022b). With a density of approximately 1.98 kg/m^3, CO_2 is about 1.67 times denser than air (Righi et al., 2022; Wałęsa et al., 2022). It cannot be liquefied below 5.1 atm, existing only as a gas or solid under standard conditions. Notably, CO_2 undergoes sublimation, transitioning directly between gas and solid (dry ice), making it useful as a cooling agent. At pressures above its triple point (5.69 bar and 217 K), it can exist as a liquid, and beyond its critical point, it becomes a supercritical fluid with valuable properties for applications in food, chemical, and medical industries (Cockrell and Trachenko, 2022; Muhunthan et al., 2023).

2.2. Applications of CO_2

CO_2 is employed across multiple industries, including food, oil, and chemicals. Its commercial uses are varied, with one of the most significant applications being the production of carbonated beverages, where CO_2 is infused to create fizziness (Chen et al., 2022; Wang et al., 2023a). These applications are detailed in Table 1.

3. Greenhouse gas

A GHG is defined as a gas in a planet's atmosphere that can absorb and emit infrared electromagnetic radiation, a process known as the greenhouse effect (Prairie et al., 2018; Sharma et al., 2021). The natural GHGs found in Earth's atmosphere include water vapor, CO_2, methane (CH_4), nitrous oxide (N_2O), and O_3 (Akbari, 2025; Huili et al., 2024; Kabange et al., 2022; Mwanake et al., 2024; Peacock et al., 2017). However, human activities—particularly the combustion of fossil fuels—have led to increased concentrations of these gases (Burnham, 2021; Gholami et al., 2020; Jiang et al., 2022). Without them, the average surface temperature of Earth would be −18 °C, making them crucial for maintaining a suitable temperature for the planet.

3.1. Greenhouse gas effect

The greenhouse effect is a natural and essential atmospheric process in which GHGs—such as water vapor, CO_2, and O_3—absorb and re-emit infrared radiation (Karalis and Kanakoudis, 2023; Kirren et al., 2022; Nair et al., 2023). This phenomenon helps retain heat within the Earth's atmosphere, ultimately causing an increase in the planet's surface temperature (Fu et al., 2021). When sunlight reaches the Earth, part of it is absorbed by the Earth's surface, warming the planet, while the rest is reflected back toward space in the form of infrared (heat) radiation. Instead of allowing all of this heat to escape, GHG molecules absorb a portion of it and re-radiate the energy in all directions, including back toward the Earth's surface. This process traps heat in the lower atmosphere, much like the glass panels of a greenhouse, hence the term “greenhouse effect”. Over time, increasing concentrations of GHGs, particularly CO_2 due to human activities like fossil fuel combustion and deforestation, intensify this natural effect, causing more heat to be retained. This results in rising global temperatures and contributes to broader climate change impacts, such as extreme weather events, sea-level rise, and changes in precipitation patterns (Chong and Wang, 2020; Nguyen et al., 2022; Sekhar et al., 2021; Wei and Wang, 2020). It's important to clarify that, although plants absorb CO_2 during photosynthesis, the earlier claim that “chlorophyll produces infrared and ultraviolet rays which interact with oxygen to generate CO_2″ is a misunderstanding. In reality, plants remove CO_2 from the atmosphere, helping to mitigate the greenhouse effect rather than contribute to it. As shown in Fig. 4, the accumulation of GHG in the atmosphere directly correlates with increased average temperatures across various regions of the globe, reinforcing the urgency of reducing GHG emissions to limit future warming.

GHGs, including water vapor, CO_2, CH_4, nitrogen oxides, and halocarbons, play a crucial role in trapping heat within the Earth's atmosphere (Chen et al., 2024; Li et al., 2024; Wang et al., 2023b). Human activities—particularly industrial and agricultural practices such as burning fossil fuels and deforestation—have contributed to an increase in these gases and a subsequent rise in global temperatures (De Vita et al., 2024). While CH_4 and chlorofluorocarbons (CFCs) are more effective at trapping energy in the atmosphere, CO_2 is considered the most significant GHG due to its higher concentration (Bhatti et al., 2024; K. Sarmah et al., 2023). Some scientists critique this perspective, arguing that climate forecasts rely on computer models and that the exact behavior of weather patterns cannot be completely predicted. Nonetheless, research demonstrates that the greenhouse effect has been significantly amplified due to rising GHG emissions (Bai et al., 2021; Guo and Liu, 2022; Kumar et al., 2023; Zhong et al., 2023).

3.2. Human-induced greenhouse gases

Over time, the concentration of GHGs has risen significantly. Human activities, particularly the release of CO_2, have led to higher levels of these gases (Arango Hoyos et al., 2023; Baiswar et al., 2023; Jiang et al., 2023; Lin et al., 2023). Key sources of GHG emissions from human activities include the burning of fossil fuels and deforestation, both of which contribute to the increase in CO_2 levels (Filonchyk et al., 2024; Okedere et al., 2021).

This chart depicts the share of anthropogenic GHGs derived from eight different source categories, according to the Global Emissions Database for Climate Research (Iqbal et al., 2024; Karami et al., 2025; Z. Ma et al., 2023; Shakoor et al., 2020). The values provide a succinct summary of global annual GHG emissions for the year 2023, with 72% attributed to CO_2, 20% to CH_4, 5% to N_2O, and 3% to other gases (P. Chen et al., 2024; Hsieh et al., 2021; Lanari et al., 2024; M. Li et al., 2021; Macharia et al., 2021; Ross et al., 2020). Fig. 5 presents comparative data for these three primary GHGs.

Table 1
Major industrial applications of CO_2.

Row	Industry	Description
1	Chemical Industries	In the chemical industries, CO_2 is primarily utilized as a feedstock in the production of urea. To a lesser extent, it is also used in the production of methanol and other products, such as metal carbonates and bicarbonates. Derivatives of carboxylic acids, such as sodium salicylate, are produced through the Kolbe-Schmitt reaction with CO_2. Additionally, electrochemical methods for producing fuels from CO_2 using renewable energy sources have been explored, allowing for the conversion of CO_2 into transportable fuels suitable for conventional combustion technologies.
2	Food Industries	CO_2 is used as a food additive and regulator in the food industry, with approval from the European Union, the United States, Australia, and New Zealand. One of its applications is in the production of candies like rock pop, which are made under pressure with CO_2 and produce gas bubbles upon dissolving in the mouth. Additionally, during the bread-making process, CO_2 is generated by baker's yeast through the fermentation of sugars, leading to an increase in dough volume.
3	Beverages	CO_2 is used to produce carbonated soft drinks and soda water. In the past, the carbonation of beer and wine occurred naturally through fermentation; however, many producers today utilize recycled CO_2 to carbonate these beverages. In the production of bottled and draft beer, CO_2 is typically transferred from storage tanks in a cold room to a taping system at the bar.
4	Inert Gas	CO_2 is one of the most commonly compressed gases used in pneumatic systems and portable pressure tools. It is also employed in welding environments. Although CO_2 reacts with metals to produce oxides, resulting in welds that are more brittle than those created in inert gas environments, it is widely used in the automotive industry due to its lower cost compared to inert gases like argon and helium.
5	Fire Extinguishers	CO_2 can be used to extinguish flames. This gas does not react chemically; instead, it suffocates the flame by displacing oxygen. CO_2 fire extinguishers are particularly effective for electrical fires and are commonly used in IT infrastructure rooms, as CO_2 does not damage equipment and does not pose a suffocation hazard.

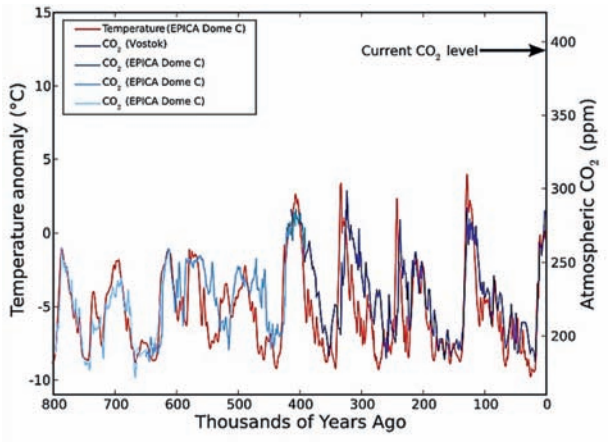


Fig. 4. Direct relationship between warming and CO_2.

4. Analysis of greenhouse gas emissions

An analysis of global energy consumption patterns reveals that the major sources of GHG emissions—particularly CO_2—are closely linked to the extensive use of fossil fuels (Chen et al., 2023; Pita et al., 2020). Among the most significant contributors are petroleum-derived fuels, including motor gasoline (used in cars), jet fuel (used in aircraft), kerosene (used for heating and lighting), distillate and residual fuels (used in industrial processes and heavy transport), and liquefied petroleum gases (LPG). In addition to fuel consumption, electricity generation remains one of the largest contributors to CO_2 emissions, especially when power plants rely on coal, oil, or natural gas for energy production (ElGalad et al., 2018; Ozoh et al., 2018). These processes involve the burning of carbon-rich fuels, which release substantial quantities of CO_2 into the atmosphere.

Moreover, vehicle emissions have shown a consistent upward trend in recent years, reflecting the growing number of cars, trucks, and other modes of transportation on the roads. This increase in transportation-related emissions further amplifies the contribution of fossil fuel consumption to the overall GHG footprint. Fig. 6 visually represents this ongoing rise in CO_2 emissions from various fossil fuel sources and transport activities, highlighting the urgent need for cleaner alternatives and emission reduction strategies.

4.1. Petroleum product

The oil and petrochemical industries are crucial components of the oil and gas sector and rank among the major sources of GHG emissions, particularly CO_2 (Abuov et al., 2022; Biswas et al., 2024; Gavurova et al., 2021; Zhao et al., 2022a). This is primarily due to their reliance on complex chemical processes and significant energy consumption. These industries utilize advanced chemical methods to manufacture products such as plastics, paints, rubbers, and protective materials, resulting in the release of considerable amounts of CO_2 into the atmosphere (Fig. 7). Moreover, fossil fuels, including natural gas and oil, provide the energy needed for these processes, and their combustion contributes to substantial CO_2 emissions (Ata et al., 2023; Nov et al., 2023; Zaidi et al., 2018). The operation of energy-intensive machinery and large equipment further exacerbates energy consumption and increases CO_2 emissions (Bor et al., 2022; Mawejje, 2023; Wang and Sun, 2024; Xu and Chen, 2022). Consequently, the petrochemical sector is one of the largest contributors to CO_2 emissions, highlighting the urgent need for strategies and technologies to manage and reduce these emissions in order to support environmental conservation and mitigate ecological effects (Zhao et al., 2022b).

The transformation of crude oil into gasoline, diesel, and jet fuel is a complex process within the oil and gas industries, conducted through refineries and petrochemical facilities (Chansiriwat et al., 2022; Eswaran et al., 2021; Zargar et al., 2017). This process involves the distillation of crude oil, which separates it into various components, including gasoline (used for vehicles and energy generation), diesel (used for vehicles and industrial equipment), and jet fuel (used in aircraft) (Deshmukh et al., 2023; Moretti et al., 2023; Xu et al., 2018). When these fuels are burned in engines and turbines, they emit CO_2 and other GHGs into the atmosphere (Yi et al., 2022). The refining of oil is a crucial element of operations in the oil and gas sector and plays a vital role in meeting global energy and transportation demands (Shah et al., 2024).

4.2. Power generation

In recent years, CO_2 emissions have risen dramatically due to human activities (Cao et al., 2024). A primary contributor to this increase is the extensive reliance on fossil fuels for energy production, as further examined below (see Fig. 8). To mitigate these emissions, proactive measures are essential (Džermeikaite et al., 2024; Džermeikaitė et al., 2024). These actions include embracing clean energy sources such as solar and wind power. Furthermore, it is important to decrease dependence on fossil fuels and promote public transportation, along with cleaner transport alternatives (Dhar et al., 2020; Ni et al., 2020; Sarmah et al., 2023).

To assess the emissions of pollutants such as CO_2, the initial focus is on electricity generation plants (Kang et al., 2019; Oteng-Abayie et al., 2024; Schwenk-Nebbe et al., 2021; Tavakkoli et al., 2022; Zhang et al., 2024). Riemer (1996) has presented data regarding the costs, efficiencies, and pollutant emissions for a representative sample of these power plants (see Table 2). This data encompasses both existing and emerging technologies. A critical element of any study is recognizing the potential need for CO_2 capture from these power plants (Jiang et al., 2020; Siegelman et al., 2019).

- The pulverized coal (PC) power plant, one of the most prevalent types of power generation facilities, serves as a benchmark for evaluating alternative technologies (Liu et al., 2022). This type of plant is equipped with flue gas desulfurization systems that help mitigate pollution (Wu et al., 2021, 2023; Xu et al., 2024a). Analyses related to this power plant also consider subcritical steam conditions and the effects of supercritical steam cycles. These characteristics have established the PC power plant as a standard for comparison with other energy production methods and as a foundation for evaluating the efficiency of various technologies in multiple research studies (Eder et al., 2024; Jaradat, 2023; Khan et al., 2023).
- The natural gas combined cycle (NGCC) power plant is a well-established and widely employed technology examined in this study (Oh et al., 2021). In this power generation facility, natural gas is burned in a gas turbine, which operates alongside a steam turbine. This combined process enhances energy production efficiency and is recognized as the most efficient method analyzed. The NGCC power plant emits the least amount of CO_2 per kilowatt-hour of electricity generated and is regarded as the most cost-effective method of electricity generation due to its access to inexpensive gas (Bui et al., 2023; Kok and Haselhoff, 2023).
- The integrated gasification combined cycle (IGCC) power plant exemplifies emerging technologies aimed at reducing CO_2 emissions for a sustainable future (Chakraborty et al., 2023; Wang et al., 2023c). This type of facility employs a gasifier

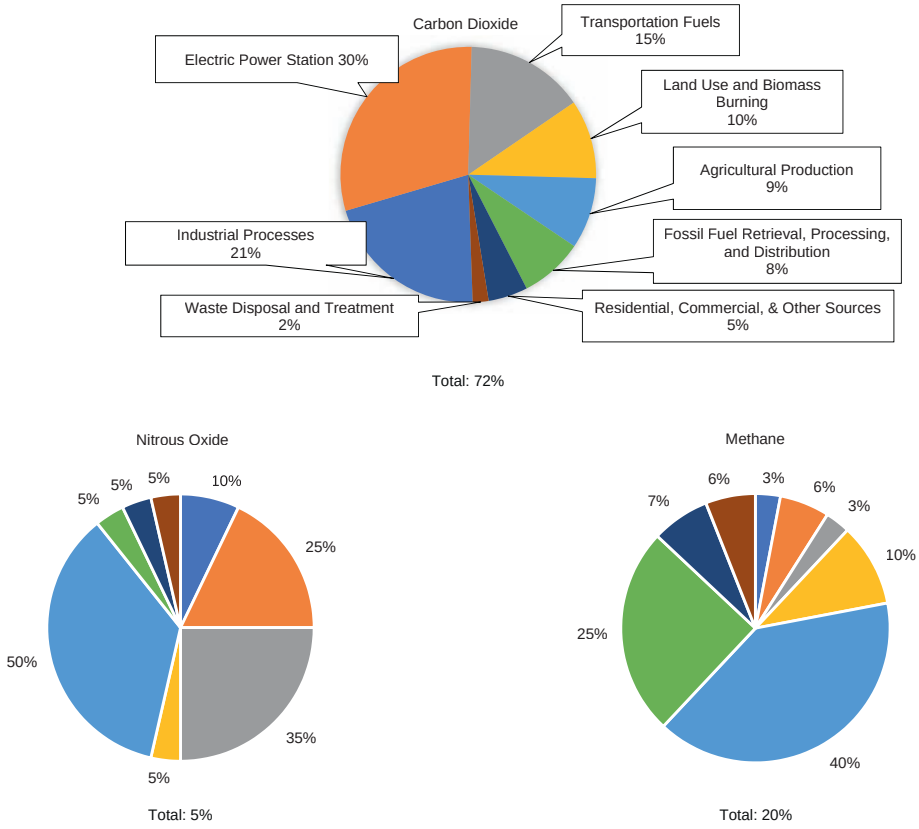


Fig. 5. Global distributions of GHGs at 8 different time intervals for the year 2023.

that processes coal slurries (He et al., 2022; Kuznetsov et al., 2023; Nyashina et al., 2023). Furthermore, various modifications, such as the type of gasifier and the conversion of syngas CO to CO_2, have been assessed in this analysis (Hou et al., 2024; Salem and Paul, 2023). This technology is recognized as an innovative solution for minimizing GHG emissions and has the potential to improve efficiency while decreasing costs.

- The combustion of coal in an oxygen-rich environment, coupled with the recovery of CO_2, has been proposed as a viable long-term strategy (Jung et al., 2023). These designs are recommended due to the higher concentration of CO_2 in the flue gas, which facilitates its capture (Cha et al., 2023). This approach is especially important for achieving objectives to reduce GHG emissions and improve the efficiency of combustion processes in power plants. By adopting this technology, it is possible to mitigate the environmental impacts associated with coal combustion and effectively manage CO_2 emissions (Jeong et al., 2024; Mercado et al., 2023).

Enhancements in efficiency across each design can lead to a significant decrease in CO_2 emissions; for example, a 1% increase in efficiency corresponds to approximately a 2% reduction in CO_2 emissions (Jia et al., 2024; Xiao et al., 2023; Xiong et al., 2022). The NGCC system offers lower electricity generation costs and comparatively reduced CO_2 emissions (Sproul et al., 2020). When considering coal-fired power plants, opting for an IGCC design for CO_2 capture is more advantageous than using a traditional PC power plant. Foundational studies in electricity generation have established the groundwork for future research and helped identify knowledge gaps (Li et al., 2024). These gaps include evaluating innovative options such as natural gas combustion in turbines with CO_2 recycling, assessing the competitiveness of hybrid gasifier/combustor designs utilizing supercritical steam cycles, and investigating alternative methods for oxygen production (Khosravi et al., 2023).

4.3. Transportation vehicles

Petroleum products encompass a variety of substances derived from crude oil, serving diverse economic and industrial purposes. These products include motor gasoline for automobiles, jet fuel for aircraft, kerosene and distillate fuels for heating and various industrial applications, residual fuels for furnaces and industrial processes, and LPG utilized in the chemical industry, among others. The combustion of motor gasoline in vehicles and jet fuel in aircraft results in the release of CO_2 into the atmosphere (He et al., 2022; Wu et al., 2023a,b). Additionally, vehicles operating on these fuels contribute further to the rise in GHG emissions, including CO_2 (Roest et al., 2020). Overall, the increased consumption of these petroleum products in industrialized societies leads to a persistent rise in CO_2 and other GHG emissions, exacerbating global environmental challenges (Fig. 9).

Overall, the use of gasoline and jet fuel is concentrated in the transportation sector, specifically for road and air travel. Diesel fuel is utilized across various sectors, including electricity generation, oil refining, cement manufacturing, heavy-duty vehicles, maritime activities, and rail transport. LPG are employed in oil refining as well as in both residential and commercial settings. Additionally, fuel oil is used in electricity generation, oil refining, and maritime activities. Consequently, an increase in the consumption of any particular fuel suggests a rise in related activities, although it can also be influenced by political shifts, such as

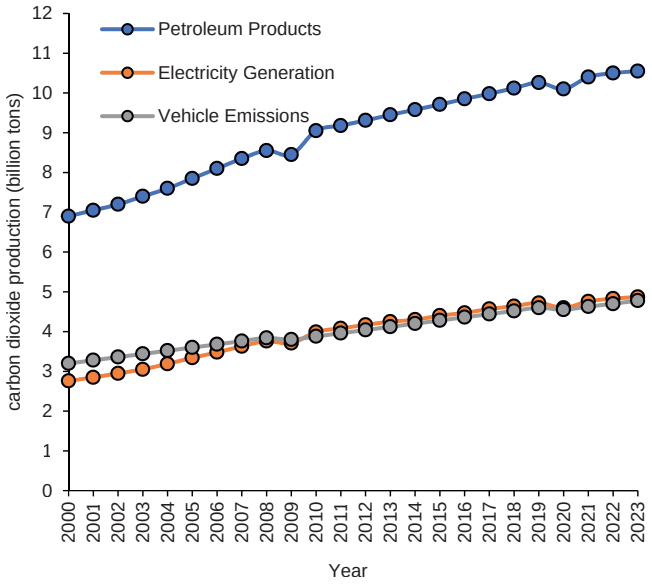


Fig. 6. CO_2 emissions from fossil fuels, electricity generation, and vehicle emissions in different years.

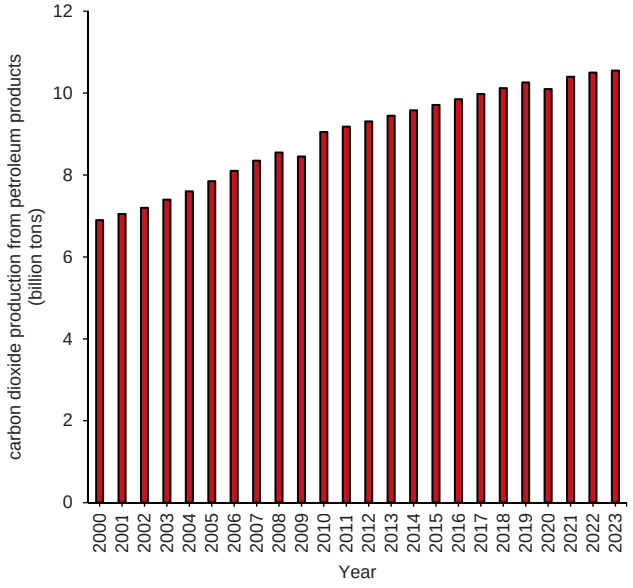


Fig. 7. CO_2 emissions from fossil fuels in different years.

changes in the fuel type designated for specific applications (Ghasemi et al., 2024; Ordóñez et al., 2022; Wang et al., 2023d).

5. CO_2 capture, storage and utilization

Following the separation of CO_2, the subsequent processes typically involve its disposal, sequestration, or utilization (Ning et al., 2023; Zhou et al., 2022a,b). CO_2 generally needs to be transported from its production source, such as industrial power plants, to the designated storage or utilization location (ElMekawy et al., 2016; Hu et al., 2024b; Singh et al., 2023). It is worth noting that CO_2 separated from chemical facilities may be converted into other chemicals on-site, as these facilities are equipped for such

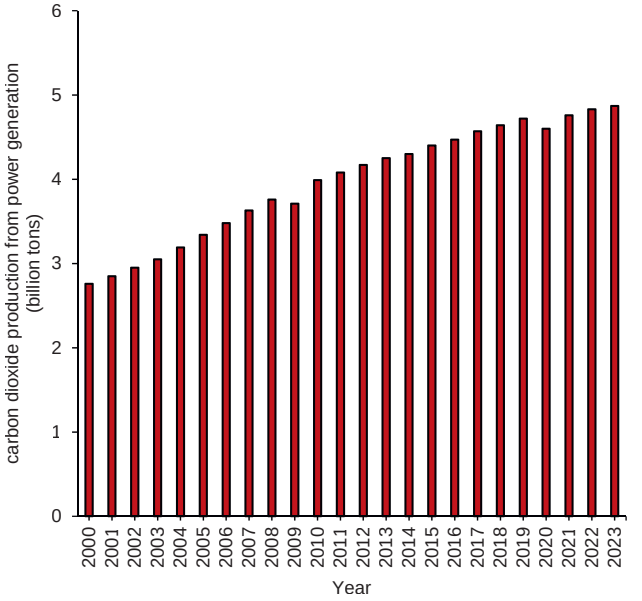


Fig. 8. CO_2 emissions from electricity generation in different years.

Table 2
Electricity generation costs for the four base cases.

	Efficiency (%)	CO_2 conc. (% dry)	Generation Cost (mills/kWh)
PF + FGD	39.9	14	49
NGCC	52.0	4	35
IGCC	41.7	7	52
CO_2 recycle	32.8	91	78

processes (Diab et al., 2024). If on-site conversion is not feasible, CO_2 can be transported via pipeline systems or stored underground in depleted oil and gas reservoirs (Fareed et al., 2023). Currently, approximately 5–7 million tons of CO_2 are stored underground each year, primarily through enhanced oil recovery methods (Ebrahimi et al., 2024; Wei et al., 2023). However, this process is still being thoroughly investigated due to potential risks to both human safety and the environment. For example, gradual or sudden large-scale leakage of CO_2 can negate the advantages of separation efforts (King et al., 2024). Additionally, increased underground pressure might trigger minor seismic events. Numerous studies highlight the various interactions that may occur with organic and inorganic materials at the storage site (Fraenza et al., 2023). For instance, carboxylic acids can significantly affect the hydration of reservoir rocks, thereby influencing both storage capacity and containment integrity. Research on the effectiveness of storage practices in depleted shale reservoirs is ongoing, as these formations possess limited coverage space and can serve dual purposes as storage sites and barriers (Ebrahimi et al., 2025; Li et al., 2024). The presence of numerous wells also facilitates the easy conversion of these wells into CO_2 injection points (Akbari et al., 2025; Chakraborty et al., 2021).

5.1. CO_2 Mitigation Techniques implementation requirement

Mitigating climate change can be achieved through the effective utilization and storage of CO_2 (Hu et al., 2024a**).** Fig. 10 outlines ten strategies for CO_2 utilization and storage. Various methods can be employed for this purpose, including chemical production,

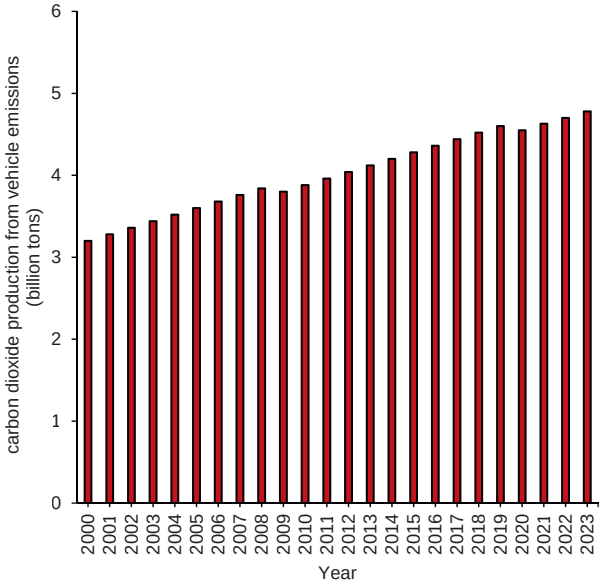


Fig. 9. CO_2 emissions from vehicle emissions in different years.

ocean storage, geological sequestration, mineralization, and other techniques (see Fig. 10).

While existing systems for CO_2 capture are available, the options remain somewhat limited. As a result, the technologies evaluated include those still in the development phase. Each capture technology detailed below has been analyzed in relation to the four types of power plants outlined in Table 2.

- **Gas Absorption Using Molecular Sieves:** A crucial aspect of this process is the release of gas in a closed system following adsorption. In all cases examined, a pressure change is favored over a temperature change for gas release, as it allows for quicker reuse of the adsorbent. The adsorption of CO_2 by an adsorbent is most effective when the gas concentration ranges from 400 ppm to 15,000 ppm, which is generally lower than the concentrations found in power plants (Li et al., 2024; Rosu et al., 2020). Due to its limited capacity and low selectivity, adsorption is not considered an attractive option for capturing CO_2 from conventional power generation processes (Das et al., 2023a,b).
- **Physical and Chemical Absorption:** Various solvents have been assessed for each type of power plant (Cichowska-Kopczyńska et al., 2023). For low partial pressures of CO_2 in flue gases, a chemical solvent, such as monoethanolamine, is preferred (Talei et al., 2024; Wang et al., 2023; Ziobrowski and Rotkegel, 2022). In contrast, a physical solvent is more advantageous at high partial pressures of CO_2. In both scenarios, if the flue gas contains substantial amounts of SO_2 (as is the case with coal-fired power plants), additional processes are required to minimize excessive solvent loss (Gu et al., 2020; Shi et al., 2020).
- **Use of Cryogenic Processes:** This approach is practical only when the CO_2 concentration in the flue gas is high, which may occur in future IGCC designs (Dowson et al., 2021; Wang et al., 2022). Cryogenic processes offer the advantage of producing liquid CO_2, which is ready for transportation via pipeline (Mankar et al., 2021).
- **Membranes:** Membranes are already employed in commercial applications, such as hydrogen separation, but further advancements are needed for their widespread use in CO_2 capture (Alami et al., 2023). The potential for reducing their currently high costs is still uncertain. One advantage of membranes is their lower energy requirements compared to other absorption methods. A promising approach involves combining membranes with chemical solvents (Arshad et al., 2024; Goren et al., 2024; Khoiruddin et al., 2024; Kunalan and Palanivelu, 2022; Zhang et al., 2024b).

A variety of potential technologies for CO_2 capture are available, and the costs and performance of the primary options have been assessed (Akeeb et al., 2022; Jana et al., 2023). This evaluation has led to the identification of the most suitable capture technologies for each type of power plant (Cao et al., 2024). A critical consideration in CO_2 capture is the additional energy required, which typically reduces the overall efficiency of energy production by about 10% (Peltier et al., 2024; Roefs et al., 2019). This factor is a significant drawback and should be included in calculations regarding the amount of CO_2 emissions mitigated and the economic aspects of capture (Jiang et al., 2024; Orlov et al., 2022; Zhang et al., 2024c,d). Table 3 presents the advantages and disadvantages of four CO_2 absorption methods.

To effectively reduce GHG emissions through CO_2 absorption, it is crucial to develop suitable storage methods (Prananto et al., 2020). The selection of storage options primarily depends on geographical location rather than the specific type of power plant or absorption technology employed. Four principal disposal methods have been investigated:

- **Ocean Disposal:** This approach involves injecting CO_2 at significant depths in the oceans. Due to the varying physical and chemical characteristics of water at different depths, CO_2 can dissolve and gradually migrate back to the ocean surface. This method is considered a viable option for CO_2 storage, leveraging the oceans' ability to absorb GHGs and the elevated pressure found at these depths. However, it is essential to consider the environmental effects and potential alterations to marine ecosystems associated with this method (Finnegan et al., 2024; Ma et al., 2023; Rodrigues et al., 2023).
- **Aquifer Disposal:** This method involves injecting CO_2 into subsurface aquifers. It is considered a promising solution for CO_2 storage, as aquifers typically possess sufficient permeability and can securely hold CO_2 under high-pressure conditions. Implementing this technique requires comprehensive geological assessments to ensure effective CO_2 storage within the aquifers and to prevent any potential leakage to the surface (Addassi et al., 2022; Ahmadi and Chen, 2019; Coelho et al., 2023; Xiao et al., 2023).
- **Disposal in Depleted Oil/Gas Reservoirs:** This approach involves injecting CO_2 into depleted oil and gas reservoirs. The structure of these reservoirs enables secure CO_2 storage, minimizing the risk of leakage into the surrounding environment. Furthermore, this method not only facilitates CO_2 storage but can also enhance oil and gas extraction processes, thereby providing a dual-purpose solution (Abu-Bakri et al., 2024; Al-Shargabi et al., 2022; Bao et al., 2020; Ni et al., 2023).
- **Solid Storage in a Thermal Insulation Tank:** This method involves converting CO_2 into a solid form and storing it in a thermal insulation tank. It is considered a safer option because it minimizes the likelihood of leakage and subsequent CO_2 emissions into the environment. However, the substantial costs associated with the production and maintenance of solid CO_2, along with the significant energy requirements for this process, present considerable challenges (Kim et al., 2024; Liu et al., 2024; Ta et al., 2023).

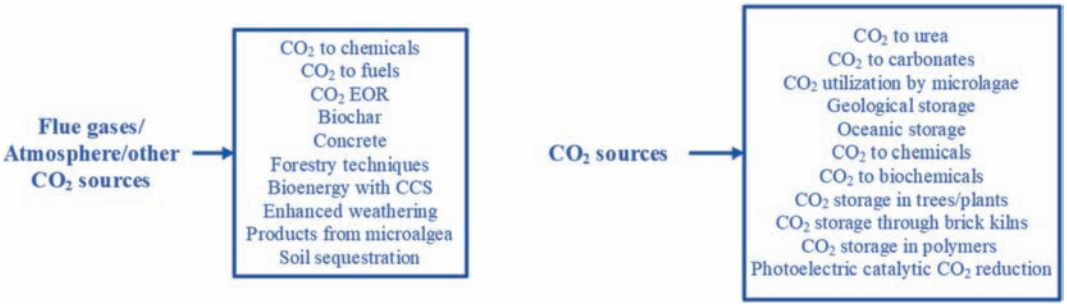


Fig. 10. Ten pathways for carbon capture (left), CO_2 mitigation techniques (right).

Table 4 presents the advantages and disadvantages of the four main CO_2 disposal methods:

While various CCUS techniques have been explored, it is essential to evaluate them through a critical lens to determine their practical viability. Absorption using molecular sieves, for example, demonstrates high selectivity but suffers from low capacity and limited scalability for industrial applications. Physical and chemical absorption methods are more scalable and effective under different pressure conditions, yet their operational costs and solvent regeneration demands are considerable. Cryogenic separation, though highly efficient at high CO_2 concentrations, is energy-intensive and therefore less favorable for large-scale deployment. Membrane technologies offer a promising low-energy alternative; however, current systems lack the robustness and economic feasibility needed for full-scale integration. Furthermore, environmental trade-offs such as the risk of solvent leakage, energy penalties, and potential land and water usage must be weighed when choosing an appropriate CCUS method. Future advancements should aim to optimize energy input, cost-effectiveness, and environmental sustainability across these diverse technologies.

Some researchers propose that the issue of carbon emissions can be mitigated by increasing the utilization of renewable energy sources (Yi, 2023). However, even if renewable energy becomes competitively priced with conventional energy sources, the widespread adoption of these alternatives may still require ongoing dependence on fossil fuels (Grossmann et al., 2023; Lu et al., 2024; Smarte Anekwe et al., 2024). Others argue that a solution to the challenges posed by fossil fuel combustion lies in the limitations of fuel supply, predicting that rising fossil fuel costs will compel a shift toward alternative energy sources. This perspective suggests that policy should be oriented toward allowing fossil fuel resources to deplete naturally, with high fossil fuel prices catalyzing the development of renewable energy options. Nonetheless, this argument presupposes that fossil fuels will become scarce before the cumulative impacts of GHGs in the atmosphere reach economically unsustainable levels. We believe this assumption is misguided. In the foreseeable future, it is likely that additional fossil fuel reserves will be identified as currently untapped resources become technically and economically viable for extraction. As a result, at current extraction rates, it could take several centuries for existing resources to be exhausted. Moreover, rapidly industrializing countries like China and India show minimal interest in moving away from their relatively inexpensive coal reserves, which account for 20% of the world's total reserves.

The process of absorbing CO_2 requires the implementation of highly efficient, selective, and cost-effective technologies that are easy to deploy and have a low environmental footprint. For several decades, CO_2 absorption has been conducted at a scale of millions of tons annually; however, further enhancements are necessary. Most existing methods rely on the absorption of CO_2 in amine solutions, which can effectively remove CO_2 in the presence of various gas compounds (Kim et al., 2023; Nguyen et al., 2023; Ramondo and Di Muzio, 2022). Nonetheless, these methods face challenges such as high operational costs, equipment corrosion, and a reduced lifespan of the amines used (Ntaflos et al., 2024). Emerging techniques increasingly focus on physical or chemical absorption, utilizing materials such as activated carbon, amines, metal oxides, alkaline metals, and ionic liquids. These innovative methods are characterized by attributes such as rapid absorption and desorption rates, low energy consumption, ease of operation, and minimal energy requirements for regeneration (Ab Rahim et al., 2023).

There are two fundamentally different mechanisms by which materials can take up other substances: adsorption and absorption. Although these two terms are often confused, they refer to distinct physical processes. Adsorption is the process in which molecules accumulate only on the surface of a material, without entering into its inner structure. This surface-level interaction is usually driven by weak intermolecular forces, such as van der Waals forces. An everyday example of adsorption is activated carbon capturing pollutants from air or water by holding them on its surface. In contrast, absorption occurs when molecules penetrate deep into the internal structure of a material. During this

Table 3
Advantages and disadvantages of four CO_2 capture methods.

Capture Method	Advantages	Disadvantages
Absorption using Molecular Sieves	• Possibility of rapid gas release in closed systems • Suitable for high concentrations of CO_2	• Limited capacity and low selectivity • Inefficient for typical concentrations in power plants
Physical and Chemical Absorption	• Variety of solvents for different conditions • Suitable performance at high and low pressures	• Requires additional processes in the presence of SO_2 • High cost of solvents and the need for regeneration
Utilization of Cryogenic Processes	• Production of liquid CO_2 ready for transportation • High efficiency at high CO_2 concentrations	• High energy requirement for cooling • Limitation in use for low concentrations
Membranes	• Requires less energy for operation • Usability in commercial applications	• Need for further development for large-scale application • High current costs and uncertainty in cost reduction

Table 4
Advantages and disadvantages of four CO_2 capture methods.

Disposal Method	Advantages	Disadvantages
Ocean Disposal	• High absorption capacity at ocean depths • Potential for reducing CO_2 concentration in the atmosphere	• Environmental impacts on marine ecosystems • Instability over time
Aquifer Disposal	• Safe storage in underground aquifers • Ability to retain CO_2 at high pressure	• Need for detailed geological studies • Risk of CO_2 leakage into groundwater
Disposal in Oil/Gas Reservoirs	• Dual-use potential of reservoirs for oil and gas extraction • Effective CO_2 storage	• Need for reservoir status assessment • Costs associated with maintenance
Solid Storage	• Reduced risk of CO_2 leakage • Higher safety compared to other methods	• High costs of production and maintenance • High energy consumption in the conversion process

process, the molecules become fully incorporated into the bulk of the absorbing substance and often form stronger interactions, including chemical bonds or reactions. For example, a sponge soaking up water demonstrates physical absorption, while gases dissolving in liquids often involve both physical and chemical absorption. In summary, adsorption is a surface-level phenomenon, while absorption involves full uptake into the material's body. This distinction is important in fields such as gas capture, catalysis, and material science. Fig. 11 visually illustrates these two mechanisms, helping to clarify how each process operates at the molecular level.

Recent research has examined microporous systems, focusing on how pore size and cross-sectional area affect the adsorption of CO_2. Findings from this research demonstrate that microporous and mesoporous carbons can adsorb substantial quantities of CO_2 at various pressures under room temperature conditions (Sevilla et al., 2018). For instance, at a pressure of 30 bar, these materials can adsorb between 32 and 33 mmol of CO_2 per gram, while at 50 bar, this figure rises to 44–49 mmol. These studies underscore the significance of micropores relative to the overall large cross-sectional area in achieving effective CO_2 adsorption (Borisut et al., 2024; Lu et al., 2022).

Incorporating NPCs can enhance the adsorption of CO_2 and improve selectivity for CO_2 compared to N_2 (Abdelnaby et al., 2023; Q. Li et al., 2021). This enhancement is attributed to increased surface polarity and improved CO_2 adsorption capabilities resulting from acid-base interactions and dipole-quadrupole interactions. However, the typical synthesis of NPCs involves expensive nitrogen-containing polymers. To mitigate these costs, monomers such as pyrazole and benzimidazole, which can be produced more easily and economically, may be employed (Liu et al., 2023; Yoshimoto et al., 2022).

Flue gases—gases released from industrial processes or power plants after fuel combustion—typically have high temperatures ranging from 150 to 400 °C. Therefore, any materials used to capture CO_2 from these gases must be able to withstand and function efficiently under such thermal conditions. To meet this requirement, medium-temperature adsorbents are employed. Materials such as Na_2CO_3, K_2CO_3, and MgO doped with Cs_2CO_3 have shown effective CO_2 adsorption performance within the 100–400 °C range. These properties make them especially suitable for capturing CO_2 immediately after combustion, when flue gases are still hot (Xu et al., 2024b). In addition, when MgO is combined with other metal oxides, such as Al_2O_3 orTiO_2, the resulting composite materials can perform efficiently at slightly lower temperatures—below 200°C—expanding their usability in various industrial settings.

Another promising approach involves using porous polymers that are infused with polyethylene imine (PEI). Research has shown that adjusting the amount of PEI and controlling moisture levels can significantly enhance the CO_2 adsorption capacity of these materials. The interaction between CO_2 molecules and the nitrogen-rich structure of PEI boosts the overall performance of the adsorbent (Priyadarshini et al., 2023). Furthermore, mesoporous silica materials—which are silica-based substances featuring highly ordered pore structures—exhibit unique adsorption properties and are available in a variety of shapes and forms. These characteristics make them suitable platforms for further modification and use in CO_2 capture technologies, as illustrated in Fig. 12. The remaining items illustrated in Fig. 10 are thoroughly and accurately detailed in Table 5. This table aims to offer a clear and concise overview of the pertinent information and data.

5.2. CO_2 utilization

While underground storage is viewed as the most rapid and extensive solution within a linear economy, its link to a circular carbon economy is established through the utilization and transformation of CO_2 into materials, chemical products, and energy (Fig. 13).

It is important to acknowledge that, despite the implementation of extensive programs (over 200 million tons per year), these efforts remain significantly inadequate compared to the global CO_2 emissions of 37,000 million tons per year. The conversion of large quantities of CO_2 can only be achieved when utilization processes are integrated with renewable energy sources. Nature has always eliminated CO_2 from the atmosphere through photosynthesis, as agricultural products and various plants naturally absorb CO_2 and sunlight while releasing oxygen. However, the rapid pace of recent industrial and social development has rendered the natural system incapable of managing anthropogenic CO_2 effectively. Among natural systems, microalgae exhibit the highest potential for absorbing and converting CO_2 into biomass, making them a promising solution for CO_2 stabilization (Thanigaivel et al., 2022; Xu et al., 2023). Different species of microalgae can utilize CO_2 or its derivatives, such as bicarbonate or carbonate, and their capabilities can be enhanced through various technologies. These include thin semi-permeable liquid-liquid membranes and photobioreactors, which promote photoautotrophic growth by incorporating small amounts of sugars. However, if pollutants like SOx and NOx are introduced directly, it is crucial to keep their concentrations below a threshold level that varies with environmental conditions to prevent detrimental effects on the algae's metabolism (Cao et al., 2023; Leszczyński et al., 2022).

From the perspective of chemical transformation, the conversion of CO_2 faces both thermodynamic and kinetic challenges due to its considerable stability (G° ~ −394 kJ/mol). To facilitate this conversion into a range of compounds—including linear and cyclic carbamates, isocyanates, and urea's (C–N bonds), as well as linear and cyclic carbonates (C–O bonds) and acids and esters (C–C bonds)—it is crucial to employ a high-energy reaction partner (such as amines, alkenes, alkynes, and dienes) along with suitable catalysts to enhance the reaction process. Table 6 presents a

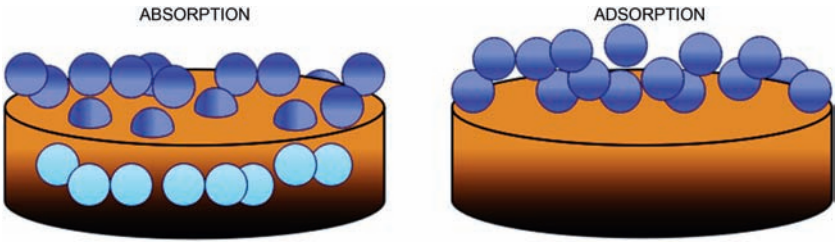


Fig. 11. Adsorption and absorption of molecules on an active substrate.

summary of the utilization of CO_2 in the formation of chemical bonds and in photocatalytic reduction processes.

6. Future research

Addressing GHG emissions through the capture and storage of CO_2 produced by power plants can be accomplished using various methods. However, the costs associated with these processes may be substantial, and significant uncertainties remain regarding the consequences of implementing such technologies. Currently, the costs and performance of these technologies can be evaluated against other CO_2 reduction strategies. While uncertainties related to the technology have decreased, important questions persist, including the potential for significantly lowering CO_2 capture costs, environmental impacts, the long-term security of CO_2 storage, the production of chemicals that heavily utilize CO_2, and how full-cycle fuel costs compare with alternative reduction options. Addressing these questions necessitates applied research into storage solutions, further exploration of potential CO_2 applications, and the encouragement of innovative concepts in combustion and capture technologies. Some of the emerging questions have been addressed in Table 7.

Table 7 presents a collection of questions along with their corresponding answers regarding gas production processes and the factors contributing to their increase. These questions and answers have been designed to enhance discussions surrounding gas production and emissions, specifically analyzing the main reasons for the rise in these gases.

International collaborations have demonstrated the potential to substantially reduce the impacts of CO_2 emissions, along with a clearer understanding of the costs and implications associated with the implementation of these technologies. However, several significant issues remain unanswered. To tackle these challenges, the second phase of the GHG Research and Development Program initiated by the International Energy Agency (IEA) has recently begun, garnering support from a growing number of countries and organizations (Rojas-Rueda et al., 2024). Future research in this area will focus on broadening global impact assessment studies, exploring the reduction of additional GHGs, and conducting more in-depth investigations into the capture, utilization, and disposal of CO_2. Ongoing efforts include studying CH_4 emissions and their mitigation strategies, applications of fuel cells, pre-combustion carbon reduction, hydrogen production, chemical applications, gasification, forestry, and the economic implications of global warming (Dang et al., 2024).

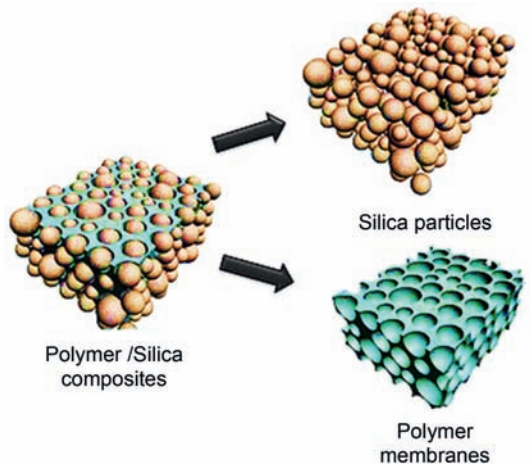


Fig. 12. Mesoporous silica polymer.

6.1. Life-cycle assessment

Life-cycle assessment (LCA) is a crucial tool used to evaluate the environmental impact of carbon capture, utilization, and storage (CCUS) technologies throughout their entire life cycle—from raw material extraction to capture, transport, storage, and possible reuse of CO_2. Studies have shown that although CCUS can significantly reduce net carbon emissions, its overall sustainability depends on various factors such as energy requirements, material use, and the source of captured CO_2. For instance, if fossil-fuel-derived energy is used to operate capture units, the benefits of CO_2 reduction may be partially offset. Therefore, incorporating renewable energy into CCUS processes is essential to minimize the system's carbon footprint and enhance its environmental effectiveness.

6.2. Techno-economic analysis

Techno-economic analysis (TEA) assesses the technical feasibility and economic viability of CCUS technologies. It considers key performance indicators such as capital and operational costs, energy efficiency, CO_2 capture rate, and return on investment. TEA has revealed that high initial capital expenditures and operating costs—particularly for solvent regeneration, compression, and transportation—are major barriers to large-scale adoption. However, advancements in material science, modular capture systems, and integration with renewable energy sources are expected to lower these costs over time. Moreover, TEA can help policymakers and investors identify the most cost-effective pathways for scaling up CCUS technologies.

6.3. Policy instruments and market incentives

The large-scale deployment of CCUS requires supportive policy frameworks and economic incentives to overcome financial and market barriers. Carbon pricing mechanisms—such as carbon taxes and emissions trading systems—create a direct financial signal for emitters to invest in carbon reduction technologies. In

Table 5
Methods of CO_2 utilization and storage.

No.	Category	Description
1	Mineral carbonation	The utilization of various types of membranes separates CO_2 gas from flue gas mixtures. Aqueous mineral carbonation, facilitated by CO_2 separation membranes, converts the separated CO_2 into carbonates using different rocks and minerals such as dunite, olivine, antigorite, and lizardite. This method can significantly contribute to reducing CO_2 emissions. As an evolving technology, mineral carbonation is employed as a permanent method for CO_2 storage. Various approaches to mineral carbonation, including single-stage, two-stage, and acid dissolution methods, are currently under investigation. By-products and mineral nutrients can also be utilized in cement production. Generally, direct mineral carbonation is preferred over indirect carbonation, and this technology is recognized as a permanent CO_2 storage solution applicable anywhere, particularly in areas close to CO_2 emission sources.
2	CO_2 to urea	This method is recognized as the optimal approach for the permanent storage of CO_2 on a large scale. In this process, CO_2 reacts with ammonia to form carbamates, which are then decomposed into urea and utilized as fertilizer by plants. The use of urea as fertilizer for agricultural products has been validated, and it has been demonstrated that CO_2 can be stored on a large scale through this process, with no possibility of return. This method is typically employed in the fertilizer production sector, where CO_2 is produced as a byproduct in the ammonia production process. Moreover, CO_2 from other industries that emit this gas, such as cement and steel manufacturing, can collaborate with fertilizer industries to convert it into urea fertilizer, as fertilizer production relies on the presence of CO_2.
3	Utilization of CO_2 in microalgae	Microbial algae absorb CO_2 effectively. Various growth characteristics have been observed for these algae, which tend to increase with rising CO_2 concentrations. The biomass produced by these algae can be repurposed in the combustion process. Microbial algae outperform terrestrial plants in this regard. A biological process can convert plant hemicellulose into other compounds. Additionally, biodiesel can be produced from ethanol through the infiltration of microbial algae. Microbial algae farms can be artificially expanded to enhance CO_2 storage, and this action can be accompanied by the production of biodiesel from the algae.
4	Enhanced oil recovery	The utilization of CO_2 in the enhanced oil recovery (EOR) process, although not constituting permanent storage, is commonly practiced. This method entails temporary constraints and the possibility of leakage. Excess CO_2 generated from gas refining facilities may be employed in fertilizer industries for urea production. One of the primary challenges in this technology is the transportation of CO_2 from emitting facilities to EOR sites. While this process involves temporary CO_2 sequestration, it still contributes to immediate CO_2 emission reduction.
5	Geological CO_2 storage	Undoubtedly, CO_2 is retained in geological storage; nevertheless, the possibility of leakage exists. Its significance in immediate CO_2 emission reduction is undeniable. It is imperative to identify the potential hazards and applications for fugitive CO_2. Thousands of individuals lost their lives due to CO_2 released after the explosion of an African lake.
6	CO_2 to chemicals	This method constitutes a permanent storage solution for CO_2 gas, converting it into ethylene carbonate, urea, and salicylic acid. In this process, CO_2 is permanently fixed in the form of chemical compounds.
7	CO_2 to biochemicals	Multiple chemical substances, including CO, CH_4, glucose, methanol, and synthetic fuels, can be produced from CO_2. The presence of enzymes is essential for CO_2 sequestration, and this process proceeds slowly. Further research is needed to discover new enzymes that can accelerate the CO_2 sequestration process.
8	Storage of CO_2 in trees and plants	In the process of photosynthesis, plants utilize CO_2, a procedure regarded as a rapid and enduring mechanism for CO_2 sequestration. There is an urgent need to augment the population of trees and plants globally to alleviate the excessive presence of CO_2.
9	CO_2 capture through brick kilns	The primary emissions from brick kilns consist of CO_2 and various particulates that impact the environment. Utilizing equipment that employs amines enables the absorption of these emissions. These methods need to be implemented extensively worldwide to reduce GHG emissions. Connecting amine systems to brick kilns can significantly reduce the release of CO_2 and particulates. Such measures can help maintain the balance of CO_2 emissions.
10	Storage of CO_2 in polymers	Polymerization reactions utilize CO_2. Various types of polymers have the capability to store CO_2 through adsorption and absorption processes. The incorporation of CO_2 into the structure of polymers enhances the CO_2 sequestration process.
11	Oceanic CO_2 storage	This initiative may pose risks that could damage marine life. However, across the globe, numerous oceans are available for this process. Oceanic CO_2 storage is performed temporarily, yet it can help reduce current CO_2 emissions and delay the global warming process.
12	CO_2 reduction using photoelectric catalysts	This emerging technology has the potential to store vast amounts of anthropogenic CO_2 emissions. To advance research and develop efficient photoelectrochemical catalysts, further investigations are needed.

parallel, government subsidies, tax credits, and feed-in tariffs can reduce investment risk and encourage private sector participation. Additionally, regulatory frameworks, including CO_2 storage liability and monitoring requirements, are essential to ensure safe and long-term sequestration. International climate agreements and national net-zero targets also play a pivotal role in shaping the policy landscape for CCUS.

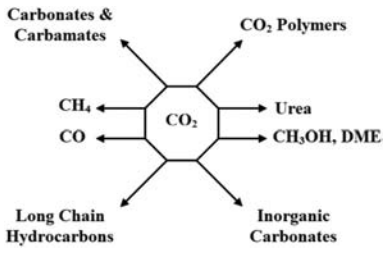


Fig. 13. Main CO_2 conversion into materials, chemicals and energy products.

Overall, integrating LCA, TEA, and effective policy tools provides a comprehensive approach to evaluating and accelerating the deployment of CCUS. These perspectives ensure that the technology is not only scientifically and economically sound but also aligned with broader environmental and social goals.

7. Conclusions

This article provides a comprehensive analysis of CO_2 emissions and the factors that influence them. It highlights the significant contributions of the oil and petrochemical industries as major sources of GHG emissions. The production of chemicals and petroleum products, along with the combustion of fossil fuels, leads to substantial CO_2 emissions, which present serious environmental challenges.

- In the energy sector, dependence on fossil fuels—particularly in coal and natural gas power plants—has intensified CO_2 emissions. Innovative technologies, such as NGCC power plants and

Table 6
Overview of CO_2 utilization in chemical bond formation and photocatalytic reduction processes.

No.	Category	Description	Equation
1	Use of CO_2 in the formation of C–N bond	CO_2 is primarily used to form C–N bonds for producing urea, carbamates, isocyanates, and various urea derivatives. These compounds are crucial in pharmaceuticals, agrochemicals, fuel additives, and polymers. Traditional methods involving phosgene are being replaced by safer routes using CO_2 and amines, which improve efficiency by removing reaction by-products. Integrated processes allow for the production of multiple chemicals from the same reaction, such as carbamic acids converting to isocyanates and then to urease. While direct reactions of amines with CO_2 for urea derivatives typically require high pressure and temperature, alternative methods have achieved high yields under milder conditions.	$RNH2 + CO_2 + R'OH$ $RNHC(O)OR' + H_2O$
2	Use of CO_2 in the formation of C–O bond	Organic carbonates, both linear and cyclic, play a crucial role in industrial applications for synthesizing important chemicals such as monomers, polymers, surfactants, plasticizers, and fuel additives. Similar to the production of carbamates, CO_2 is increasingly utilized in the synthesis of organic carbonates from alcohols, facilitated by specific catalysts that eliminate the need for toxic substances like phosgene or CO. This approach yields various types of polycarbonates, including aromatic phosgene-free variants and aliphatic forms like polypropylene carbonate and polyethylene carbonate, all derived from CO_2. Heterogeneous catalysts based on metal oxides, especially CeO_2, are highly regarded for their efficiency in converting CO_2 into dimethyl carbonate and polyols into polycarbonates. Managing water content is critical for maintaining catalyst stability and optimizing reaction equilibria. Innovative methods such as membrane reactors utilizing zeolites are being explored for separating products in ethanol-CO_2 reactions, enhancing process efficiency through continuous flow systems and maximizing surface-to-volume ratios.	$2\ ROH + CO_2$ $ROC(O)OR + H_2O$
3	Use of CO_2 in the formation of C–C bond	CO_2 reacts with nucleophiles such as oxygen and N_2, while carbanions are needed for forming C–C bonds to create carboxylic acids. Organometallic reagents possessing nucleophilic carbanionic functionality interact with CO_2 to yield carboxylic acid salts. As a carboxylating reagent, CO_2 is used to produce inorganic carbonates, which are then used for synthesizing dicarboxylic acids, mainly in the polymer industry. Additionally, photocarboxylation of organic substrates has been successfully performed using semiconductors, either on their own or supported on graphene oxide.	
4	Photocatalytic CO_2 reduction	Photocatalytic CO_2 reduction is gaining attention for converting CO_2 and water into hydrocarbon fuels, syn-gas, and polymers, producing high-energy products like HCOOH, HCHO, CH3OH, and CH_4. Key factors include light excitation properties, band structure, and charge carrier separation efficiency. While various metal systems have been tested as catalysts, they often deactivate quickly. Promising candidates are Cu(I) complexes and Ag–MgO–TiO2 composites, which benefit from Ag nanoparticles' surface plasmon resonance and MgO nanoparticles' CO_2 adsorption, enhancing photocatalytic activity and CH_4 selectivity.	

Table 7
Analysis of questions and answers regarding the production and increase of GHGs.

No.	Question	Answer and Description
1	How much has the concentration of GHGs increased in recent years?	Since the early Industrial Revolution, GHG concentrations have risen significantly, with CO_2 increasing by approximately 31%, CH_4 more than doubling, and N_2O rising by about 17%. These changes are primarily attributed to the combustion of fossil fuels for transportation, heating, electricity generation, and other human activities. Data from polar ice cores show that over the past 10,000–250 years, CO_2 levels have surged from 260 to 280 ppmv to around 370 ppmv, accompanied by a 151% increase in CH_4 and a 17% rise in N_2O. Similar increases in O_3 and other trace gases have been reported, many of which emerged in recent decades and were absent before industrialization.
2	How do scientists know that the increase in the concentration of GHGs in the atmosphere is due to human activities?	Numerous factors highlight human activities as the primary source of increasing GHG concentrations. The current rate of concentration rise aligns with human emissions, marking an unprecedented change in thousands of years of atmospheric history. Trends in carbon isotopic ratios and the distribution of CO_2 in the atmosphere also reflect the expansion of human emissions. The rapid increase in GHGs over the past century is consistent with human emission trends, which are unmatched in at least 420,000 years and possibly even 20 million years. The decrease in CO_2 molecules containing radioactive carbon-14 supports the rise in fossil fuel emissions that include “old” carbon. Changes in carbon-13 and carbon-12 ratios in the oceans further indicate human contributions, along with the north-south gradient in atmospheric CO_2 concentrations. Carbon budget models suggest that human emissions significantly influence the global carbon cycle. Studies on CH_4 and N_2O also indicate human contributions; however, uncertainties regarding natural and human processes make their exact roles less clear. Lastly, trace gases like halocarbons and sulfur hexafluoride lack credible natural sources, with strong evidence attributing concentration changes solely to human emissions.
3	The amount of CO_2 that is added to the atmosphere each year by human activities is only a small fraction of what is released from natural sources. However, how can our actions lead to a significant change in atmospheric CO_2 concentration?	Human emissions have disrupted the natural balance of CO_2 in the atmosphere, leading to significant accumulation over time. Currently, human emissions are about 28 billion tons per year, representing roughly 5% of the natural CO_2 flux, which is approximately 550 billion tons per year from sources such as plant respiration and ocean runoff. Natural emissions are balanced by absorption processes like photosynthesis. Ice core samples show that before the industrial era, CO_2 concentrations fluctuated around an average of 280 ppmv, indicating a well-balanced natural carbon budget. This imbalance due to human activities is the main cause of the 31% increase in CO_2 concentrations over the past few centuries, reflecting the cumulative human debt in the global carbon budget.
4		

(*continued on next page*)

Table 7 (*continued*)

No.	Question	Answer and Description
	Do volcanoes naturally release more CO_2 into the atmosphere each year compared to humans?	Volcanoes contribute less than 1% of human CO_2 emissions, playing a minor role in changes in atmospheric CO_2 concentrations. Historically, volcanic emissions were part of the natural cycle and reached near equilibrium before the Industrial Revolution. Currently, volcanoes release about 150 million tons of CO_2 annually, while humans emit over 22 billion tons from fossil fuels and around 6 billion tons from deforestation, making human emissions more than 100 times greater. Mount Etna is the largest volcanic source of CO_2, emitting about 25 million tons per year, whereas Mount St. Helens emits less than 2 million tons annually.
5	What human activities contribute the most GHGs to the atmosphere?	The extensive use of fossil fuels accounts for 70%–90% of human CO_2 emissions, primarily from transportation, energy production, heating, cooling, and electricity generation. Other major contributors include livestock farming, agriculture, and deforestation, resulting in over 22 billion tons of CO_2 released annually from fossil fuel combustion. Deforestation and poor land management exacerbate the situation; however, new forest growth and better soil management can help mitigate these impacts. In Canada, about one-third of GHG emissions come from energy production, split evenly between electricity generation and fossil fuel extraction. Transportation contributes 27% of emissions, construction contributes 17%, and non-electric energy use in the residential, commercial, and agricultural sectors accounts for approximately 22%. Other countries exhibit similar emission sources, but the proportions vary based on their economies, cultures, and climates.
6	Do human emissions from aerosols lead to cooling of the atmosphere and thus compensate for GHG emissions?	Human activities contribute to the production of sulfate and carbon aerosols, biomass burning particles, and dust, which can directly reflect or absorb sunlight and alter cloud processes, significantly impacting regional climates. While some aerosols cause warming and others cooling, their complex effects are not fully understood but are generally considered secondary to GHGs. As countries control aerosol emissions to reduce local air pollution, their future climate impact is expected to be smaller compared to that of GHGs.
7	Humans also release a significant amount of CO_2 into the atmosphere through respiration. Should we stop breathing to halt climate change?	The CO_2 exhaled by humans is part of the natural carbon cycle, involving the uptake of carbon from food and its release through respiration and waste. The growth of food also removes CO_2 from the atmosphere through photosynthesis. Each person consumes significant amounts of carbon from plant-based foods, meat, and fish, which is collected through the food chain. Most ingested carbon is expelled through respiration and waste, with a small portion retained for body mass accumulation, creating a minor carbon sink. After death, buried bodies contribute to a long-term carbon sink.
8	I understand that water vapor is a dominant factor in the natural greenhouse effect. Does this mean that changes in the concentration of other GHGs are insignificant?	Water vapor, which accounts for about two-thirds of natural GHGs, significantly influences climate. Its concentration changes are primarily driven by temperature variations that affect the hydrological cycle. As other GHGs increase, air and surface temperatures rise, leading to more water vapor, which enhances the warming effect. This also raises the maximum water vapor capacity of the atmosphere and accelerates evaporation from land and ocean surfaces, impacting cloud formation and the climate system. Scientists agree that the feedback from increased water vapor amplifies warming but note that its effects are complex and depend on location and time.

integrated gasification systems, have been developed to effectively reduce these emissions. Additionally, strategies such as oxygen-enriched combustion and CO_2 recycling are recognized as valuable methods for managing GHGs.

- The transportation sector also plays a crucial role in CO_2 emissions due to its reliance on petroleum fuels. The environmental impacts associated with the use of gasoline, jet fuel, and diesel underscore the urgent need for policy changes and a transition to cleaner energy and sustainable transportation options.
- A deeper understanding of CO_2 emission dynamics across various sectors, combined with the development of cutting-edge technologies, offers promising avenues for mitigating the adverse effects of climate change. International collaboration and investment in sustainable technologies are essential for achieving a green and resilient future.
- Moreover, CO_2 separation and storage are critical strategies for combating climate change and reducing GHG emissions. After the separation process, options such as disposal, capture, or utilization come into play, with the transportation of CO_2 from industrial sources to storage or conversion facilities representing a vital step. While existing CO_2 capture technologies are available, further advancements are needed to improve efficiency and reduce associated costs.
- Investigating CO_2 utilization also contributes to the establishment of a circular carbon economy, emphasizing the importance of incorporating renewable energy sources into CO_2 conversion processes. Natural systems, such as microalgae, hold substantial potential for CO_2 capture and conversion; however, addressing the thermodynamic and kinetic challenges to achieve effective conversion is crucial.

In conclusion, effective CO_2 management requires a multifaceted approach that integrates advanced capture technologies, strategic storage solutions, and sustainable utilization methods. This comprehensive strategy will not only support a sustainable energy landscape but also help address the escalating challenges posed by climate change.

CRediT authorship contribution statement

Ali Akbari: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project

administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hossein Sarvi:** Investigation. **Mahdi Maleki:** Investigation. **Sina Bahreyni:** Investigation. **Reza Azimi:** Investigation. **Alireza Radpour:** Investigation.

Conflict of interest statement

The author declare that they have no conflicts of interest regarding the publication of this paper. No financial, personal, or professional affiliations have influenced the research presented in this study.

Abbreviations

CCU	Carbon Capture and Utilization
CCS	Carbon Capture and Storage
CFC	Chlorofluorocarbon
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
GHG	Greenhouse Gas
CCUS	Carbon Capture, Utilization, and Storage
H_2CO_3	Carbonic Acid
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
LCA	Life-cycle assessment
LPG	Liquefied Petroleum Gas
N_2	Nitrogen
N_2O	Nitrous Oxide
NGCC	Natural Gas Combined Cycle
O_3	Ozone
PC	Pulverized Coal
PEI	Polyethylene Imine
SDG	Sustainable Development Goal
TEA	Techno-Economic Analysis

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