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Review

A State-of-the-Art Review on Technology for Carbon Utilization and Storage

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Abstract: Carbon capture utilization and storage (CCUS) technologies are regarded as an economically feasible way to minimize greenhouse gas emissions. In this paper, various aspects of CCUS are reviewed and discussed, including the use of geological sequestration, ocean sequestration and various mineral carbon mineralization with its accelerated carbonization methods. By chemically reacting CO_2 with calcium or magnesium-containing minerals, mineral carbonation technology creates stable carbonate compounds that do not require ongoing liability or monitoring. In addition, using industrial waste residues as a source of carbonate minerals appears as an option because they are less expensive and easily accessible close to CO_2 emitters and have higher reactivity than natural minerals. Among those geological formations for CO_2 storage, carbon microbubbles sequestration provides the economic leak-free option of carbon capture and storage. This paper first presents the advantages and disadvantages of various ways of storing carbon dioxide; then, it proposes a new method of injecting carbon dioxide and industrial waste into underground cavities.

Keywords: carbon capture utilization and storage; mineral carbon mineralization; carbon microbubbles sequestration; geological sequestration; industrial waste

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1. Introduction

Since the beginning of the industrial revolution, the combustion of fossil fuels has resulted in the release of significant quantities of greenhouse gases such as carbon dioxide, nitrous oxide, methane, ozone, and chlorofluorocarbons [1]. As a gradual but direct result, global temperatures have risen by approximately 1.5 °C, primarily because of emissions of anthropogenic greenhouse gases [2,3]. Carbon dioxide (CO_2), a greenhouse gas generated in large quantities by human activity, is the leading contributor to climate change [4]. An increase in temperature of 1.5 °C or more can be expected to exert far-reaching and drastic consequences for water and food availability, human health, ecosystems, coastlines, and biodiversity [5]. Global warming, a crucially important environmental issue, has caused the loss of biodiversity, water, and land, while adversely affecting several sustainability criteria [6].

Several authoritative agencies have released the latest data related to carbon dioxide emissions. According to the International Energy Agency (IEA) analysis, carbon dioxide emissions of worldwide in 2021 rose by 6% to reach their highest-ever level of 36.3 billion tonnes, as the global economy recovered vigorously from the effects of the COVID-19 pandemic, there was a significant dependence on coal as the primary source of energy to support this growth. To limit global warming to approximately 1.5 °C (2.7°F), the Intergovernmental Panel on Climate Change (IPCC) scenarios suggest that worldwide emissions of greenhouse gases must be reduced by 43% before 2030 [3]. Additionally, the American National Oceanic and Atmospheric Administration reports that the current concentration of atmospheric CO_2 is 416 parts per million (ppm) and increasing at a rate of 2.8 ppm annually [7]. Therefore, reducing CO_2 emissions is necessary for human survival.

Nevertheless, the world's energy demand is projected to increase by more than 28.6% by 2040 [8], indicating that brand-new energy sources including hydrogen, wind, and solar must replace fossil fuels. Even in light of that necessity, achieving such a transition in a short time is expected to be challenging [9].

As a practical method for lowering atmospheric CO_2 concentrations, carbon capture and storage (CCS) is at the center of attention [10]. Storage is a vital step in the development of CCS systems. Earlier review papers detailed numerous physicochemical techniques for effective CO_2 storage and emphasized the challenges posed by diverse techniques and initiatives [11–14]. For instance, many investigations have been reported of CO_2 storage techniques such as mineral carbonation (MC) [15], offshore storage [16], and geological storage [17]. However, Michael Economides, an energy specialist, claims that CCS, comprising numerous components such as collection, gathering, and injection, is an impractical solution for controlling CO_2 because of insurmountable hurdles related to physical needs and cost [18].

A similar strategy is employed for carbon capture, utilization, and storage (CCUS) that have gained significant attention as a promising approach to mitigating greenhouse gas emissions. While all three components (capture, utilization, and storage) are important, the utilization of captured carbon dioxide has been highlighted as a crucial element in the CCUS strategy. Carbon utilization not only reduces the net amount of carbon dioxide released into the atmosphere but also creates value-added products, thus providing economic incentives for the implementation of CCUS technologies [19]. Table 1 provides a brief summary of the advantages and disadvantages of CCS and CCUS as well as a comparison of their CO_2 capture capabilities, which are general estimates and can vary depending on the specific technology and implementation used.

Table 1. Comparing CCS and CCUS.

Method	Advantages	Disadvantages	CO_2 Capture Value
CCS	Reduces carbon emissions from large point sources such as power plants and industrial processes	Requires significant energy and resources to capture, transport, and store CO_2; long-term stability of stored CO_2 and prevention of leakage are concerns	Can capture up to 90% of CO_2 emissions from the source
CCUS	In addition to reducing carbon emissions, captured CO_2 can be used in products such as chemicals and fuels, potentially creating a new revenue stream; utilization can reduce the overall cost of carbon capture	Utilization processes can require significant energy and resources; economic viability of utilization depends on various factors	Can capture up to 99% of CO_2 emissions from the source

According to a report by the International Energy Agency (IEA) [20], "utilizing captured carbon dioxide can be a game-changer for the economics of carbon capture, making it more viable for both power and industrial applications". The report also notes that carbon utilization has the potential to reduce the cost of CCUS by up to 50%, depending on the technology used and the price of CO_2 emissions. Several carbon utilization pathways have been proposed and tested, including enhanced oil recovery, mineral carbonation, and the production of chemicals and fuels. For instance, carbon dioxide can be used to enhance the recovery of oil and gas from existing wells, a process known as enhanced oil recovery (EOR), which has been shown to be economically viable in certain regions. Another pathway is the mineral carbonation of silicate minerals, which involves the reaction of carbon dioxide with silicate minerals to produce stable carbonates. This approach has been demonstrated in pilot-scale projects and has the potential to permanently store carbon dioxide in a geological form. Additionally, captured carbon dioxide can be used as a feedstock for the production of chemicals and fuels, including methanol, urea, and dimethyl ether. A study by Biswal et al. [21] explored the potential of converting captured CO_2 into methanol, which is a valuable fuel and chemical intermediate. They found that integrating carbon capture

with methanol production could significantly reduce CO_2 emissions while also generating economic benefits. Another study by Szima et al. [22] investigated the use of CO_2 in the production of synthetic natural gas (SNG) through a process called the Sabatier reaction. The study demonstrated the potential of CCUS-SNG to not only reduce CO_2 emissions but also contribute to energy security and resource utilization. Additionally, the utilization of CO_2 for the production of building materials, such as concrete, has gained attention in recent years. A study by Li et al. [23] investigated the use of CO_2 in the production of lightweight concrete, which has potential environmental and economic benefits. Overall, the utilization of CO_2 is a promising component of CCUS, offering both environmental and economic benefits. In conclusion, carbon utilization is a critical component of the CCUS strategy as it not only reduces greenhouse gas emissions but also provides economic incentives for the implementation of CCUS technologies. Consequently, until renewable energy is used more extensively, carbon capture utilization and storage (CCUS) technologies by converting captured CO_2 into valuable products are regarded as an economically feasible way to minimize greenhouse gas (GHG) emissions.

In a CCUS supply chain, CO_2 is collected and compressed at the source facility before being transported to a location for use or injection for geological sequestration. Reportedly, CCUS has the potential to cut global CO_2 emissions from the energy sector by 20% [24]. Although many studies have evaluated CCS or CCUS operations, few have considered storing CO_2 and industrial waste together in underground spaces, such as abandoned coal mines and Underground Coal Gasification (UCG) cavities.

This study addresses the difficulties and promise presented by CCUS research from the perspective of CO_2 recycling. The following is the structure of this paper: Section 2 presents a discussion of CO_2 storage methods in CCUS. Section 3 describes CO_2 mineralization methods. Section 4 introduces and explains the method of simultaneous injection of CO_2 and industrial wastes into underground goaf for mineralization. Section 5 discusses the CCUS research gaps and challenges for the future. Finally, Section 6 provides the conclusion.

2. CO_2 Storage Methods

This discussion offers an in-depth analysis of the relevant literature, advancements, and debates related to different CCUS methodologies. Figure 1 portrays the main CO_2 storage methods which are commonly acknowledged as CCS/CCUS technologies. They have the capability of lowering CO_2 emissions. However, to achieve the predicted net-zero CO_2 emissions objective by 2050, their present worldwide deployment remains insufficient [25]. Various strategies for CO_2 sequestration including physical, biological, and chemical storage possibilities are being investigated because the captured CO_2 must eventually be stored to eliminate its effects [26,27]. Biological storage refers to the process by which living organisms absorb and store carbon, converting CO_2 from the atmosphere into organic matter through photosynthesis. This process is essential for regulating the carbon cycle and maintaining a stable climate. Biological storage includes the carbon sequestration in plants [2] and soil carbon sequestration [28]. Plants, algae, and other photosynthetic organisms play a key role in biological storage by converting CO_2 into organic compounds, such as carbohydrates and proteins [29]. These compounds can be stored within the organism's tissues or released into the soil, where they can be further broken down and stored as organic matter [30]. Physical storage includes geological storage [31,32] and ocean storage [33]. Mineral carbonation is a chemical storage method that involves the reaction of CO_2 with minerals [31]. Physical and chemical storage will be detailed in the following chapters. Carbon dioxide storage can be achieved through three main methods: (i) geological storage in deep geological formations, (ii) ocean storage in deep ocean water, and (iii) mineral storage in the form of mineral carbonates [31].

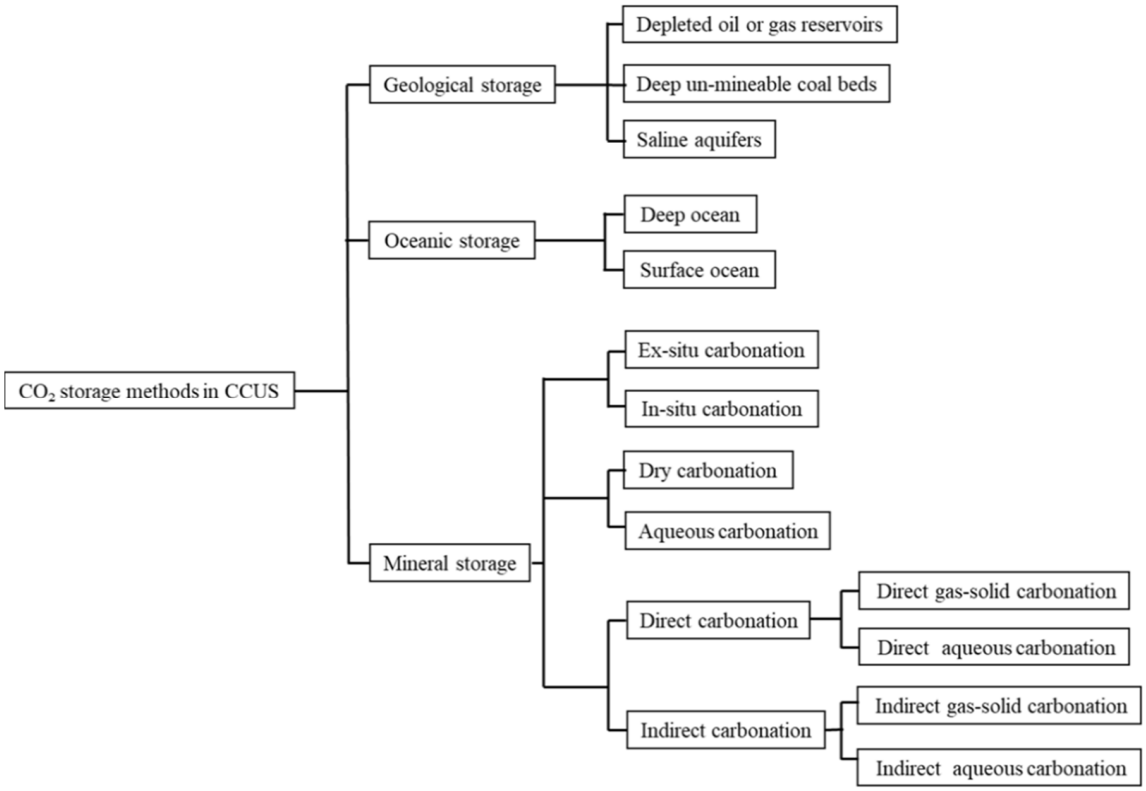


Figure 1. CO_2 storage methods.

2.1. Geological Storage

Similarly to the natural storage of fossil fuels in nature, CO_2 geological storage involves the injection of CO_2 into a suitable underground geological formation or stratum at a specific depth. During the last decade, reports of the literature describing investigations of geological CO_2 storage have increased considerably [34]. Over 1 million tonnes of CO_2 are now being stored at 14 different places throughout the world [35]. Depending on the research location, the estimated global CO_2 storage capacity ranges from 100 to 20,000 gigatons CO_2 [36]. Saline aquifers, deep unmineable coal beds, and depleted oil and gas reservoirs are considered the best places for CO_2 geological storage [31].

2.1.1. Depleted Oil or Gas Reservoirs

Geological storage is an extensively employed technique for enhanced oil and gas recovery (EOR/EGR) due to its potential for large-scale storage capacity [37,38]. In fact, depleted oil and gas reservoirs' storage of CO_2 is regarded as an extremely effective storage option, illustrating a few of its many benefits: (i) extensive prior research and exploration during hydrocarbon exploration stages, which has allowed for the determination of storage capacity; (ii) existing subterranean and surface infrastructure, such as pipelines and injection wells, that is useful for storage processes with minimal modification [39–41]; and (iii) the oil and gas industry's widespread usage of CO_2 injection as an EOR technology, which can be leveraged for storage processes [42].

For EOR, CO_2 is used to increase the reservoir pressure, thereby creating sufficient driving force to extract the remaining oil from active wells. Furthermore, the injection of CO_2 can be utilized to recover natural gas (methane, CH_4) from coal beds. The basic principle behind this method is that the introduction of CO_2 can displace CH_4 from the coal while simultaneously storing the CO_2 within the porous structure of the coal bed [43]. The injection of CO_2 for EOR is supported by mature technologies. Moreover, studies have investigated various aspects of the processes, including migration simulation [44], geochemical modeling [45], and leakage/risk assessment [46]. However, environmental

considerations associated with EOR include the creation of massive volumes of water that might include radioactive materials and hazardous heavy metals [47].

2.1.2. Deep Unmineable Coal Beds

Coal bed methane (CBM) reservoirs are naturally occurring formations of coal that contain large amounts of methane gas trapped within the coal matrix. When coal bed methane is extracted, it not only removes the methane gas but also reduces the pressure within the coal seam. This pressure reduction can cause the release of CO_2 that is adsorbed onto the coal surface. This process is known as CO_2 desorption and can lead to the release of significant amounts of CO_2 into the atmosphere [48].

However, coal beds also have the potential to store large amounts of CO_2 through a process called CO_2 sequestration. This process involves injecting CO_2 into unmineable coal seams where it is adsorbed onto the coal surface, replacing methane gas. The CO_2 is then trapped within the coal matrix and stored underground for long periods of time, potentially mitigating the release of CO_2 into the atmosphere. The technique of CO_2 storage in coal seams involves utilizing the void space created by the removal of methane. A comprehensive review of this method was conducted by White et al. [43], which highlighted key issues such as estimation of potential storage capacity, storage integrity, physical and chemical processes, as well as environmental health and safety. The storage potential of deep unmineable coal beds for CO_2 sequestration is significant. In fact, coal beds have been estimated to have the potential to store over 500 gigatons of CO_2 globally. A study by Hu and Cheng [49] estimated the potential of CO_2 storage in deep unmineable coal seams in China to be 69.5 Gt. Similarly, another study by Liu et al. [50] estimated the CO_2 storage capacity in the Illinois Basin to be 66.7 Gt. Furthermore, coal beds are often located near power plants, which could provide a convenient source of CO_2 for sequestration.

The long-term storage stability of CO_2 in deep unmineable coal beds is dependent on several factors, such as the coal type, coal rank, depth, and pressure. Hu and Cheng [49] reported that deep coal seams with high-rank coal have higher CO_2 storage capacity and better storage stability due to their low permeability and high sorption capacity. Additionally, the geological sequestration of CO_2 in deep unmineable coal seams has been found to be effective in the long term, as reported by Bao et al. [51].

One of the primary technical advantages of CO_2 sequestration in deep unmineable coal beds is the existing infrastructure and knowledge from the coal bed methane industry. Additionally, CO_2 injection can enhance methane production, which can offset some of the costs associated with CO_2 sequestration [52]. Furthermore, the use of unmineable coal beds for CO_2 sequestration can also avoid potential environmental impacts associated with coal mining activities [51].

However, there are several challenges associated with CO_2 sequestration in deep unmineable coal beds. One of the main challenges is the potential for CO_2 leakage, which can occur due to faults or fractures in the surrounding rock formations [50]. Additionally, the costs associated with CO_2 injection, monitoring, and verification can be high. There is also the need for the development of regulatory frameworks and policies to ensure the safe and effective implementation of CO_2 sequestration in deep unmineable coal beds [51].

In summary, CO_2 sequestration in deep unmineable coal beds has significant potential for mitigating CO_2 emissions from power plants and other industrial sources. However, it also presents significant technical challenges that must be addressed to ensure the safety and effectiveness of this approach.

2.1.3. Saline Aquifers

Deep saline aquifers, located at depths of 700–1000 m below ground level, are known to contain high-salinity formation brines [53]. While these saline aquifers are not commercially valuable, they can serve as a useful storage site for injected CO_2 captured from the CCS process. Indeed, saline aquifers are considered an important option for CO_2 storage due to their vast storage capacity. It is estimated that they are capable of sequestering

10,000 gigatons (Gt) of CO_2, which is equivalent to the emissions from large stationary sources for over 100 years [54,55]. Saline aquifers, in contrast to other storage sites, often have a larger spatial distribution and broader regional coverage.

Saline aquifers have the potential to store up to 10,000 gigatons of CO_2, which is equivalent to 20–500% of the predicted emissions by 2050, as reported by Davison, Freund, and Smith [56]. According to Pruess et al. [57], the long-term CO_2 storage capacity in saline aquifers is approximately 30 kg/m^3. Another important advantage of these aquifers is that they are easily accessible from most existing CO_2 capture sites, which makes the CO_2 sequestration process much more cost-effective. Additionally, these aquifers are often highly mineralized and are not suitable for supplying drinking water, making them a viable option for CO_2 storage without compromising the availability of freshwater resources [56]. Rock porosity is a crucial factor for CO_2 sequestration, as it enables the injection and storage of CO_2 by displacing brine or gas from pore structures. Deep saline aquifers are typically abundant in both porosity and permeability, making them the most suitable locations for CO_2 storage [58]. Although saline aquifers have the potential to store a large amount of CO_2, there is still less knowledge available about their storage characteristics compared to other geological storage sites, such as coal seams and oil fields. Yang et al. [59] conducted a review on the characteristics of CO_2 sequestration in saline aquifers, including the behavior of CO_2 in different phases, the interactions of CO_2 with water and rock, and the mechanisms of CO_2 trapping, such as hydrodynamic trapping, residual trapping, solubility trapping, and mineral trapping [60–62]. Extensive investigations have been conducted on the parameters that influence the mineral trapping of CO_2 during its sequestration in brines [63]. Szulczewski et al. [64] assessed pressure buildup during injection and CO_2 entrapment within the pore spaces of deep saline aquifers to estimate CO2 storage capacity. Nevertheless, due to inadequate understanding of the geochemical behavior in saline aquifers, global CO_2 storage capacity estimates remain imprecise [65]. Economically, many saline aquifers are currently considered less desirable as a storage option due to the lack of necessary infrastructure, including injection wells, surface equipment, and pipelines, as well as the associated capital costs required for developing such infrastructure.

Although geological storage of CO_2 has the potential to significantly reduce greenhouse gas emissions, there are also several potential drawbacks and challenges associated with this method. One of the main concerns with geological storage is the possibility of CO_2 leakage [66]. While caprock formations are designed to prevent CO_2 from escaping, there is still a risk of leakage due to natural fractures or faults in the rock. In the event of a leakage, the stored CO_2 could potentially migrate to the surface and pose a risk to human health and the environment. Another challenge is that geological storage might entail risks such as geological structure deformation, underground water acidification, and increased incidence of earthquakes [67]. Additionally, there are also concerns around the cost and energy requirements of geological storage [66]. While this method has been used for decades in the oil and gas industry, it is still relatively expensive and energy intensive. There is also a need for the ongoing monitoring and maintenance of storage sites, which can add to the overall cost [68].

2.2. Oceanic Storage

The oceans constitute a crucially important natural carbon sink that absorbs excess CO_2. The exchange of CO_2 at the air–sea interface dissolves carbon, which is subsequently carried in seawater via the circulation of thermohaline. The physical conditions that affect ocean storage include temperature, salinity, and pressure. These conditions determine the solubility of CO_2 in seawater and the rate at which CO_2 can be transported to the deep ocean. In general, colder and saltier water can dissolve more CO_2 than warmer and fresher water. This means that the polar regions are particularly well suited for ocean storage, as they have colder and saltier water than other regions of the ocean [69]. Pressure is also an important factor in ocean storage, as it affects the solubility of CO_2 and the rate at which it can be transported to the deep ocean [70]. Additionally, CO_2 is transported to the deep

ocean via the sinking of organic material, including phytoplankton, through the biological pump [27].

Efforts have been made to replicate natural processes for carbon sequestration through two mechanisms in the ocean. The first involves pumping CO_2 straight into the deep ocean without passing the mixed layer. Despite conversations among experts and entrepreneurs, there are currently no prospects for crediting carbon trapped in the ocean. Similarly to geological storage, oceanic carbon storage involves injecting CO_2 into the deep ocean, creating liquid CO_2 lakes through the high pressure and supercritical state. Captured CO_2 might be transferred via a pipeline or ship to the ocean or seafloor for discharge. Oceanic storage has a significant theoretical CO_2 storage capacity, as the world's deep ocean trenches have the potential to store vast amounts of CO_2. The Puerto Rico trench, for example, has the capacity to store 24,000 Gt of liquid CO_2 deeper than 7 km, and the Sunda trench, located below 6 km, has the potential to accommodate 19,000 Gt of liquid CO_2, surpassing the CO_2 yield from all current global fossil fuel reserves. However, concerns have been raised that the stored CO_2 might escape back into the atmosphere [71]. Hence, it requires careful monitoring to ensure that the CO_2 does not leak back into the atmosphere [72]. The second involves adding nutrients to the surface ocean to stimulate the biological pump. Ocean fertilization involves adding nutrients to the ocean to stimulate the growth of phytoplankton, which absorb CO_2 during photosynthesis. When the phytoplankton die, they sink to the bottom of the ocean, carrying the stored CO_2 with them [73].

On the opposite side, the injection of CO_2 into the ocean could cause seawater acidification, leading to harm to marine ecosystems and leading to potentially devastating effects on marine life. According to Caldeira and Wickett [74], ocean model predictions suggest that carbon dioxide emissions to the atmosphere and ocean will cause significant chemistry changes. Since the London Convention restricted ocean storage in 2007, research in this field has been significantly reduced with considering these possibilities of the above disadvantage [34].

2.3. Mineral Storage

Mineral sequestration techniques were initially proposed by Friedel [75], who suggested accelerating the carbonation process by using high-purity CO_2. Mineral carbonation (MC) is a promising technology for carbon capture and storage (CCS) that mimics the natural weathering processes. The process involves an exothermic reaction between CO_2 and alkaline earth-metal-bearing minerals and wastes, resulting in the formation of stable carbonate minerals [76–78]. Carbonates are more thermodynamically stable than CO_2, as their standard Gibbs free energy is lower. Therefore, they are considered as a more stable form of carbon [79]. The stability of carbonates suggests that CO_2 mineral storage offers a secure and long-term solution for storing CO_2 without the need for continuous monitoring. Compared to other carbon storage methods, mineral carbonation through the reaction of CO_2 with Ca and Mg-bearing minerals, either naturally or industrially, offers several unique advantages. These include excellent long-term stability of CO_2, the creation of value-added products through the carbonation process, and the potential for in situ application by various industries [80,81].

The literature related to MC is extensive. Numerous studies have been conducted and reviewed regarding the carbon sequestration process using mineral carbonation [82]. Reviews conducted by Sipilä et al. [83] and Huijgen et al. [84] have extensively examined the initial developments in this field until 2006. A review presented by Torróntegui et al. [85] has covered relevant studies until 2010. An overview of the growth of MC of industrial wastes was presented by Bodor et al. [86]. Numerous reviews have covered the evolution and contemporary advances of MC extensively, even describing the use of different feedstock materials [82,87,88]. Moreover, notable reviews explained the MC of ultramafic mine deposits [89], steel-making waste [90], fly ash [91], and pH swing processes [92].

Recently, separate reviews of the energy costs and carbon footprints associated with various MC routes were presented by Naraharisetti et al. [93] and Ncongwane et al. [94].

However, concerns have arisen about the techno-economic aspects of many earlier studies [95,96]. Table 2 presents the estimated CO_2 storage capacities of the methods explained above.

Table 2. Estimated CO_2 storage capacity [97].

Option	Gigatons of Carbon (GTC)
Depleted oil or gas reservoirs	180–250
Deep unmineable coal beds	1–55
Saline aquifers	275–2750
Ocean storage	>5000
Mineral carbonation	Very large

3. CO_2 Mineralization Methods

Mineralization reactions can be conducted either ex situ or in situ, depending on the location of the reaction. The term "ex situ" refers to aboveground processes that require the mining and transportation of feedstock or which are conducted near an existing industrial facility. The pre-processing for carbonation in ex situ mineralization processes involves rock mining and the comminution of mineral ore. This method is preferred in areas where geological storage sites are not available [31,98,99]. In contrast, in situ mineralization processes involve injecting CO_2 into underground reservoirs, which triggers a reaction between alkaline minerals and CO_2 in geological formations [89,100]. Compared to ex situ techniques, in situ carbonation is more cost-effective, since no chemical plant is needed. Mineral carbonation can be carried out using either dry or aqueous processes. However, the dry process has slower carbonation kinetics and low conversion efficiency, making it unsuitable for large-scale applications. Nevertheless, it is still useful for developing CO_2-absorbing solid sorbents such as calcined limestone [101–103]. In contrast, among the earliest pilot-scale MC methods studied [104], the aqueous route is considered to be the most efficient for carbonate conversion in mineral carbonation. This new MC technique [93] is the most widely employed route [15].

Depending on the reaction mechanism, mineral carbonation is divisible into two types: direct carbonation and indirect carbonation. Direct carbonation involves a direct reaction between minerals and CO_2 that contain magnesium and calcium. In contrast, indirect carbonation involves the initial extraction of either magnesium or calcium with CO_2, which is followed by injecting it into the extraction solution for carbonation [83,105,106].

3.1. Direct Carbonation

Direct carbonation is a straightforward method that involves a single-stage process for carbonation [107]. The two types of direct carbonation are gas–solid and direct aqueous. During gas–solid direct carbonation, minerals react with gaseous CO_2, whereas direct aqueous carbonation involves slurries reacting with CO_2.

The dry route typically refers to processes with a low moisture content, typically less than 0.2 [108]. However, this method is hindered by slow carbonation kinetics and low conversion efficiency, making it less suitable for large-scale applications. In contrast, aqueous carbonation is a more efficient method for mineral carbonation, as discussed previously.

3.1.1. Direct Gas–Solid Carbonation

Direct gas–solid carbonation is a straightforward approach to direct carbonation that involves the reaction of gaseous CO_2 with solid minerals. Lackner et al. [106] first reported this method, which benefits include ease of designing processes and the potential for heat recovery at high temperatures [109]. However, the slow reaction rate makes this method infeasible without some optimization to accelerate the carbonation process.

Experimental findings suggest that the direct carbonation of dry rock minerals exhibits an insignificant carbonation rate, even under high temperatures and pressure [80].

According to Kwon et al. [110], the addition of moisture to the flue gas during dry carbonation processes can substantially enhance the rate of carbonation. However, the method's low CO_2 sequestration efficiency requires the use of eight tons of olivine to capture one ton of CO_2, rendering the process practically unviable and strongly constraining its wide-scale applicability.

Equation (1) describes the direct carbonation of silicates through the dry route. The Gibbs free energy values for this reaction under standard temperature and pressure have been calculated to be −44.6 kJ/mol, −43.0 kJ/mol, and −16.9 kJ/mol for wollastonite ($CaSiO_3$), forsterite (Mg_2SiO_4), and serpentine ($Mg_3Si_2O_5(OH)_4$), respectively, indicating their potential to proceed spontaneously. However, the slow reaction kinetics and low conversion rate associated with this process result in prolonged reaction times [111,112].

$$(Ca, Mg)_xSi_yO_{x+2y+z}H_{2z}\ (s) + xCO_2\ (g) \rightarrow x(Ca/Mg)CO_3\ (s) + ySiO_2\ (s) + zH_2O\ (g/l) \quad (1)$$

3.1.2. Direct Aqueous Carbonation

In addition to process parameters and pre-treatments, the selection of minerals is also an important consideration for direct aqueous carbonation. Minerals with high reactivity, such as serpentine, wollastonite, and olivine, are preferred for efficient carbonation [113]. The size and morphology of the mineral particles also affect the reaction kinetics and efficiency. Finely ground particles with a high surface area can support faster reaction rates, but they can also cause clogging and difficulties in separation from the reaction products. Therefore, some balance between particle size and reaction efficiency must be considered [114].

Another important consideration for direct aqueous carbonation is the management of reaction products, mainly the solid carbonates and the liquid effluent. The solid carbonates can be processed further to enhance their storage capacity or to facilitate their use in various applications, such as construction materials. The liquid effluent, by contrast, contains unreacted minerals and other dissolved components; it requires pre-disposal treatment to mitigate its environmental effects [113].

Overall, direct aqueous carbonation can provide distinct advantages over the dry route, including higher reaction rates, higher CO_2 uptake capacity, and lower energy requirements. However, direct aqueous carbonation also requires the careful consideration of process parameters, mineral selection, and management of reaction products and effluent.

3.2. Indirect Carbonation

The indirect mineral carbonation process involves several stages [115–118]. With acids or other solvents, the Mg or Ca ions are extracted from the mineral ore in the first step. They are then transformed into their respective hydroxides or oxides. In the second stage, these oxides or hydroxides undergo a reaction with CO_2 to produce carbonates [108].

3.2.1. Indirect Gas–Solid Carbonation

The carbonation of Mg or Ca oxides or hydroxides occurs much more rapidly compared to direct carbonation from their respective silicate forms. However, natural occurrences of Ca/Mg oxides/hydroxides are rare, necessitating their production from Ca/Mg silicates [119]. As a result, the indirect gas–solid carbonation process is employed, whereby the extracted Ca or Mg is initially converted into their corresponding oxides or hydroxides. Subsequently, these mineral oxides or hydroxides undergo carbonation in dry conditions [106].

Research has demonstrated that the conversion of $Mg(OH)_2$ to $MgCO_3$ occurs rapidly under specific conditions. For instance, the complete conversion of $Mg(OH)_2$ to $MgCO_3$ within 2 h at a temperature of 500 °C and pressure of 340 bar was reported by Lackner et al. [106]. Similarly, Butt et al. [120] observed a 90% conversion of $Mg(OH)_2$ to $MgCO_3$ at pressure of 53 MPa and a temperature of 565 °C within 30 min for a particle size of 0.1 µm.

3.2.2. Indirect Aqueous Carbonation

Compared to indirect gas–solid carbonation, the indirect aqueous route involves two consecutive reactions. First, Mg or Ca is extracted from minerals using some chemicals under acidic conditions, which is followed by carbonation of the extracted Ca and Mg under alkaline conditions. One significant advantage of mineral extraction is the potential to obtain nearly pure minerals, as extracting the reactive metal allows for the removal of other impurities present in the natural mineral core [121]. Several technologies are useful for mineral extraction, including acid leaching, molten salt leaching, caustic soda leaching, and bioleaching. For instance, using HCl can produce pure alkali earth metals. However, if the recovery of HCl is required, then it becomes considerably energy intensive. Conversely, molten salts require less energy for regeneration compared to HCl. However, molten salts are more corrosive than HCl [83]. Another indirect carbonation approach is pH swing. This method involves extracting mineral carbonate from the solid matrix under low pH conditions in the first stage. In the second stage, the pH of the extraction solution is increased to facilitate carbonate formation [122]. As previously explained, acids have the capability to extract large quantities of calcium and magnesium ions from the feedstock. However, the precipitation of calcium and magnesium carbonates is greatly influenced by pH. Hence, raising the solution pH to around 10 during the second stage of mineral extraction aids in accelerating the rate of carbonate precipitation [92]. Direct carbonation is considered a more practical option for mineral carbonation due to its simplicity in process design and lower cost compared to indirect carbonation, which requires an additional process step and the use of extraction agents.

As we introduced above, there are several techniques for mineral carbonation, including direct gas–solid carbonation, direct aqueous carbonation, indirect gas–solid carbonation, and indirect aqueous carbonation. Each of these techniques has its own advantages and disadvantages, which are summarized in Table 3.

Table 3. The advantages/disadvantages of different mineral carbonization techniques.

Mineral Carbonization Techniques	Advantages	Disadvantages
Direct gas–solid carbonation	• Direct gas–solid carbonation is a simple and straightforward process that involves the reaction of carbon dioxide with solid minerals at high temperatures and pressures. • This technique can be used with a wide range of mineral feedstocks, including ultramafic rocks, serpentinites, and mine tailings. • Direct gas–solid carbonation has the potential to sequester large amounts of carbon dioxide in a relatively short amount of time.	• The high temperature and pressure requirements of direct gas–solid carbonation can make the process energy-intensive and expensive. • The reaction rate can be slow, and the reaction may not go to completion. • The process requires a large amount of water, which may be a limiting factor in arid regions.
Direct aqueous carbonation	• Direct aqueous carbonation is a relatively low-temperature and low-pressure process that can be carried out at atmospheric conditions. • The process can be carried out using a wide range of mineral feedstocks, including serpentinites and olivine. • The reaction rate can be faster than that of direct gas–solid carbonation.	• Direct aqueous carbonation requires a large amount of water, which may be a limiting factor in arid regions. • The process requires the use of strong acids, which can be expensive and pose a risk to human health and the environment. • The process can be affected by impurities in the mineral feedstock, which may require additional processing steps to remove.

Table 3. *Cont.*

Mineral Carbonization Techniques	Advantages	Disadvantages
Indirect gas–solid carbonation	• Indirect gas–solid carbonation involves the use of metal catalysts to enhance the reaction rate and reduce the energy requirements of the process. • The process can be carried out at lower temperatures and pressures than direct gas–solid carbonation, reducing energy costs. • The use of metal catalysts can enhance the selectivity and yield of the reaction.	• The use of metal catalysts can be expensive, and the catalysts may be susceptible to deactivation over time. • The process can be sensitive to impurities in the mineral feedstock, which may require additional processing steps to remove. • The reaction rate may still be slower than that of direct aqueous carbonation.
Indirect aqueous carbonation	• Indirect aqueous carbonation involves the use of soluble metal salts to enhance the reaction rate and reduce the energy requirements of the process. • The process can be carried out at lower temperatures and pressures than direct gas–solid carbonation, reducing energy costs. • The use of soluble metal salts can enhance the selectivity and yield of the reaction.	• The use of soluble metal salts can be expensive, and the salts may be susceptible to precipitation or degradation over time. • The process can be sensitive to impurities in the mineral feedstock, which may require additional processing steps to remove. • The reaction rate may still be slower than that of direct aqueous carbonation.

3.3. CO_2 Mineralization Capacity

For mineral CO_2 sequestration, feedstocks of two readily available types might contain substantial amounts of Ca/Mg: mineral ores (primary minerals) and industrial residues (secondary materials). The following Tables 4 and 5 summarize the results of mineralization tests of some mineral ores and industrial residues. We can report their carbonization efficiency (CE) under different routes.

Table 4. Experiment parameters and carbonation efficiency by mineral ores.

Mineral Ores	Main Oxide Content %	Carbonation Route	CO_2 Vol%	Operating Conditions	CE %	Reference
Serpentine	MgO = 40.8	DAC	100	Pre-treatment: T = 630 °C Carbonation: T = 155 °C, P = 18.75 MPa, t = 0.5 h, D < 37 μm, 0.64 M $NaHCO_3$, 1 M NaCl	78	[123]
		DAC	100	Pre-treatment: T = 630 °C Carbonation: T = 185 °C, P = 11.65 MPa, t = 0.5 h, D < 37 μm, 0.5 M $NaHCO_3$, 1 M NaCl	83	
		DAC	100	Pre-treatment: T = 630 °C Carbonation: T = 185 °C, P = 11.65 MPa, t = 0.5 h, D < 37 μm, Distilled water	34	
	MgO = 45.7	DAC	100	Pre-treatment, T = 630 °C Carbonation: T = 155 °C, P = 18.75 MPa, t = 30 min, D < 37 μm, 0.64 M $NaHCO_3$, 1 M NaCl	78	[124]
	MgO = 38.7	DAC	100	Pre-treatment: T = 650 °C, Steam activated Carbonation: T = 155 °C, P = 12.77 MPa, t = 60 min, D = 75 μm, 0.6 M $NaHCO_3$; 1 M NaCl	59.4	[125]
	MgO = 43.33	IAC	100	Dissolution: T = 100 °C, t = 3 h, 1.4 M NH_4HSO_4, NH_3 Carbonation: T = 140 °C, P = 0.1 MPa, t = 60 min, D = 75 μm, NH_4HCO_3	85	[115]

Table 4. *Cont.*

Mineral Ores	Main Oxide Content %	Carbonation Route	CO_2 Vol%	Operating Conditions	CE %	Reference
	MgO = 40.1	IAC	100	Dissolution: T = 100 °C, t = 2 h, HCL Carbonation: T = 90 °C, P = 0.1 MPa, t = 60 min, D < 75 µm, NH_4OH	95.9	[126]
	MgO = 40.1	IAC	100	Dissolution: T = 100 °C, P = 0.1 MPa, t = 3 h, 1.4 M NH_4HSO_4, NH_4OH Carbonation: T = 80 °C, P = 0.1 MPa, t = 60 min, D = 75–150 µm, NH_4HCO_3	93.5	[127]
	MgO = 40.72	IAC	100	Dissolution: T = 80 °C, t = 6 h, 1 M HCl, 1 M NaOH Carbonation: T = 50 °C, P = 0.1 MPa, t = 1 h, D = 10–56 µm, 1 M Na_2CO_3	82.5	[128]
	MgO = 44.82	IAC	100	Dissolution: T = 70 °C, t = 1 h, 1 vol% H_3PO_4, 0.9 wt % $C_2H_2O_4$, and 0.1 wt % EDTA Carbonation: T = 25 °C, P = 0.101 MPa, t = 10 min, D < 75 µm, NH_4OH	65	[122]
Olivine	MgO = 49.3	DAC	10	T = 150 °C, P = 0.1 MPa, t = 0.5 h, D = 10 µm	25	[110]
	MgO = 49.7	DAC	100	T = 185 °C, P = 11.65 MPa, t = 24 h, D < 37 µm, Distilled water	91	[123]
		DAC	100	T = 185 °C, P = 11.65 MPa, t = 6 h, D < 37 µm, 0.5 M $NaHCO_3$, 1 M NaCl	84	
		DAC	100	T = 155 °C, P = 18.75 MPa, t = 1 h, D < 37 µm 0.64 M $NaHCO_3$, 1 M NaCl	38	
	Unknown	DAC	100	T = 185 °C, P = 15.2 MPa, t = 6 h, D < 75 µm	85	[104]
	MgO = 46.4	DAC	100	T = 180 °C, P = 14.08 MPa, t = 24 h, D < 100 µm	78.8	[129]
	MgO = 47.3	DAC	99.99	T = 185 °C, P = 14.08 MPa, t = 3 h, D = 30.02 µm 0.64 M $NaHCO_3$	79.7	[114]
	MgO = 50.9	DAC	100	T = 185 °C, P = 6.59 MPa, t = 6 h, D < 38 µm 2.5 M $NaHCO_3$, 1 M NaCl	84.4	[113]
	MgO = 45.3	DAC	100	T = 180 °C P = 13.17 MPa, t = 8 h, D = 20–45 µm 0.64 M $NaHCO_3$	62.3	[130]
	MgO = 48.1	IAC	100	Dissolution: T = 100 °C, t = 3 h, 1.4 M NH_4HSO_4 Carbonation: T = 90 °C, P = 0.1 MPa, t = 1 h, D = 75–150 µm	25	[110]
	NA	DAC	100	Pre-treatment: T = 630 °C Carbonation: T = 185 °C, P = 15.2 MPa, t = 6 h, D < 75 µm	62	[104]
Wollastonite	CaO = 30	DAC	100	T = 200 °C, P = 2.03 MPa, t = 15 min, D < 38 µm L/S = 2	69	[131]
	CaO = 46.6	DAC	100	T = 150 °C, P = 4.05 MPa, t = 60 min, D < 30 µm	83.5	[132]
	Unknown	DAC	100	T = 185 °C, P = 15.2 MPa, t = 1 h, D < 75 µm	80	[104]
	CaO = 46.6	IAC	99.9	Dissolution: T = 80 °C, t = 2 h, 6 M HCl Carbonation: T = 30 °C, P = 0.1 MPa, t = 1 h, D = 75–150 µm, NH_4OH	93	[133]

Table 5. Experiment parameters and carbonation efficiency by industrial residues.

Industrial Residues	Main Oxide Content %	Carbonation Route	CO_2 Vol%	Operating Conditions	CE %	Reference
Fly ash	CaO= 30.42	DAC	10	T = 25 °C, P = 0.1 MPa, t = 3 min, NH_4OH	56.6	[134]
	CaO = 29.6.0	DAC	100	T = 30 °C, P = 0.1 MPa, t = 2 h, L/S = 0.15	51.5	[135]
BOFS	CaO = 31.0	DAC	40	T = 50 °C, P = 0.51 MPa, t = 4 h, D = 63–100 µm	53.6	[136]
	CaO = 42.43	DAC	99	T = 65 °C, P = 0.1 MPa, t = 0.5 h, D < 63 µm, L/S = 20	93.5	[137]
	CaO = 46.45	DAC	30	T = 30 °C, P = 0.1 MPa, t = 20 min, D < 125 µm	90.7	[138]

Table 5. *Cont.*

Industrial Residues	Main Oxide Content %	Carbonation Route	CO_2 Vol%	Operating Conditions	CE %	Reference
SS	CaO = 41.15	DAC	100	T = 25 °C, P = 0.1 MPa, t = 120 min, D < 44 µm	89.4	[139]
	CaO = 41.15	DAC	99	T = 50 °C, P = 0.1 MPa, t = 120 min, D < 44 µm	57	[140]
	CaO = 36.37	DAC	98.9	T = 25 °C, P = 0.1 MPa, t = 1 min, D = 44 µm	38.08	[141]
	CaO = 20.6	DAC	60	T = 650 °C, P = 2.03 MPa, t = 30 min, D < 80 µm	98	[142]
	CaO = 51.11 ± 4.82	DAC	100	T = 60 °C, P = 0.1 MPa, t = 60 min, D < 44 µm, L/S = 10	68	[143]
	CaO = 54.19 ± 2.73	DAC	100		48	
	CaO= 37.2	DAC	99.5	T = 50 °C, P = 0.1 MPa, t = 4 h, D = 63–200 µm	61.6	[144]
		DAC	99.5	Pre-Sonication: 24 Hz, t = 4 h, T = 50 °C, P = 0.1 MPa, t = 4 h, D = 63–200 µm	73.2	
	CaO = 40.6	DAC	99.5	T = 50 °C, P = 0.1 MPa, t = 4 h, D = 63–200 µm	30.5	
		DAC	99.5	Pre-Sonication: 24 Hz, t = 4 h, T = 50 °C, P = 0.1 MPa, t = 4 h, D = 63–200 µm	48.5	
	CaO = 54.8	DAC	99.5	T = 90 °C, P = 0.61 MPa, t = 2 h, D < 500 µm	52	[145]
	CaO = 50.0	DAC	99.5		40	
	CaO = 44.5	IAC	13	Dissolution: T = 70 °C, t = 2 h, NH_4Cl Carbonation: T = 40 °C, P = 0.1 MPa, t = 1 h, D < 63 µm	72.8	[146]
	CaO = 38.98	IAC	100	Dissolution: T = 50 °C, P = 0.1 MPa, NH_4HSO_4 Carbonation: T = 65 °C, P = 0.1 MPa, t = 1 h, D = 75–150 µm, NH_4HCO_3	74	[147]
	CaO = 31.70	DAC	100	T = 100 °C, P = 1.93 MPa, t = 30 min, D < 38 µm Nanopure-demineralized water	74	[84]
	CaO = 34.28	DAC	100	T = 90 °C, P = 0.1 MPa, t = 4 h, D = 25–37 µm Nanopore-demineralized water	70	[148]
EAFS	CaO = 35.0	DAC	100	T = 100 °C, P = 1.01 MPa, t = 24 h, D < 150 µm	72.3	[149]
	CaO = 32.1	DAC	100	T = 25 °C, P = 0.1 MPa, t = 17 h, D = 45–75 µm	11.8	[150]
	CaO = 36.5	DAC	100	T = 30 °C, P = 0.1 MPa, t = 2 h, L/S = 0.15	33.9	[135]
	CaO= 38.5	DAC	100		15	
BFS	CaO = 44.0	DAC	100	T = 20 °C, P = 1 MPa, t = 28 d	39	[151]
	CaO = 41.5	DAC	100	T = 25 °C, P = 0.15 MPa, t = 6 h, D < 35 µm NaOH, L/S = 0.2	28	[152]
	CaO = 32.9	IAC	100	Dissolution: T = 50 °C, t = 30 min, NH_4HSO_4 Carbonation: T = 30 °C, P = 0.1 MPa, t = 1 h, L/S = 10	13	[153]
	CaO = 38.3	IAC	100	Dissolution: T = 100 °C, t = 30 min, NH_4HSO_4 Carbonation: T = 55 °C, P = 0.1 MPa, t = 0.5 h, D = 75–150 µm, NH_4HCO_3/NH_3	97	[154]
	CaO = 40.6	IAC	100	Dissolution: T = 70 °C, t = 2 h, CH_3COOH Carbonation: T = 30 °C, P = 0.1 MPa, t = 15 min, D < 10 µm, NaOH	72.5	[121]
	CaO = 32.8	DAC	15	T = 20 °C, P = 0.1 MPa, t = 24 h, D = 38–106 µm	2.2	[155]
LFS	CaO = 58.1	DAC	15		24.8	
LMFS	CaO = 49.9	DAC	100	T = 25 °C, P = 0.1 MPa, t = 17 h, D = 45–75 µm	10	[150]
PFA	CaO = 51.9	DAC	15	T = 20 °C, P = 0.1 MPa, t = 1 h, D < 100 µm	33	[156]

BOFS—blast oxygen furnace slag; SS—steel slag; EAFS—electric arc furnace slag; BFS—blast furnace slag; LFS—ladle furnace slag; LMFS—ladle metallurgy furnace slag; PFA—pulverized firing oil shale ash.

4. Simultaneous Injection of CO_2 and Industrial Waste

Abandoned coal mines refer to the production mines and mining areas where a certain mineral resource either has been depleted, is on the brink of depletion, has lost its economic value for mining, or fails to meet environmental protection standards for mining [157]. Most coal mines around the world are known to use the traditional longwall mining method introduced in the 19th century [158]. Longwall panel mining involves the progressive removal of coal from a rectangular area, resulting in the collapse of the roof and the formation of a goaf. On the other hand, the Underground Coal Gasification (UCG) process creates underground voids through the gasification of coal [159]. When UCG or mining activities have been conducted at considerable depths, the storage of CO_2 in these artificial high-permeability zones becomes an appealing option [160]. Subsidence of the ground above the goaf engenders the formation of cracks, from which CO_2 might leak upward. Considering the risks of leakage, carbon dioxide can be stored in the form of microbubbles because CO_2 injected as microbubbles not only dissolves rapidly in water: it is also little affected by buoyancy. Furthermore, the density of CO_2, even when dissolved in water is greater than that of groundwater, thereby reducing the risk of upward leakage of CO_2 [161].

This section presents a method of combining underground storage and mineral storage: CO_2 microbubble water and industrial waste are injected into mined-out areas (closed underground coal mines or goaf after UCG) to fix carbon dioxide permanently, as shown in Figure 2. This method was tested in an underground abandoned coal mine during August 2022 in Mikasa City, Japan [162], as shown in Figure 3. The storage concept for CO_2 and industrial wastes presented herein offers a synergetic approach to stabilize the mined-out stratum mechanic state for the mitigation of mining subsidence and for providing an alternative course for the unfavorable disposal of industrial wastes.

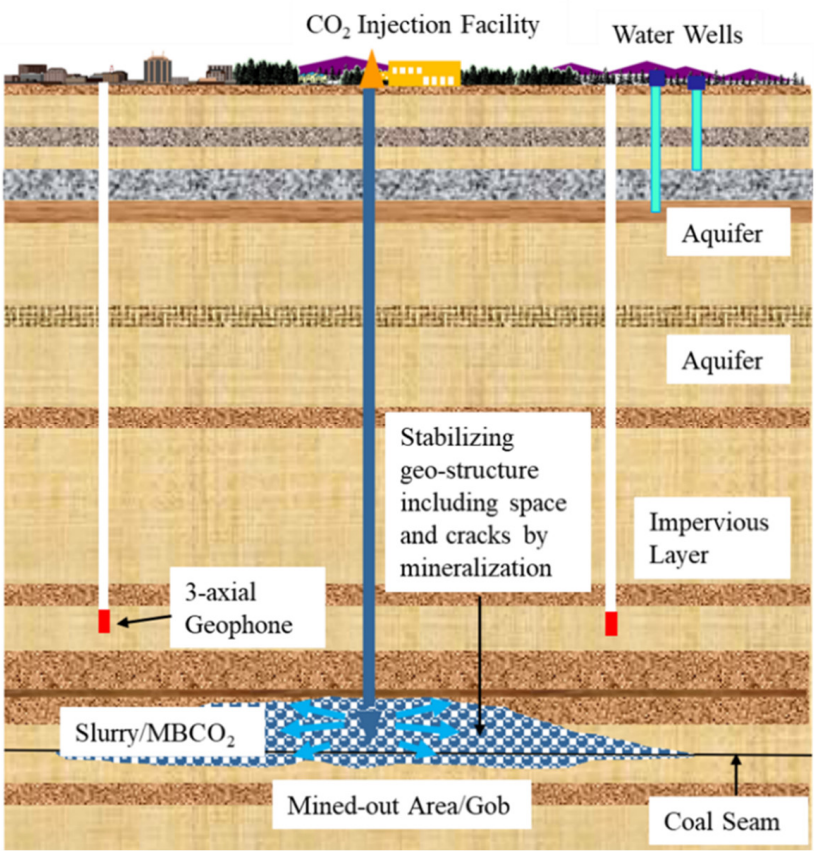


Figure 2. CO_2 storage schematic diagram.

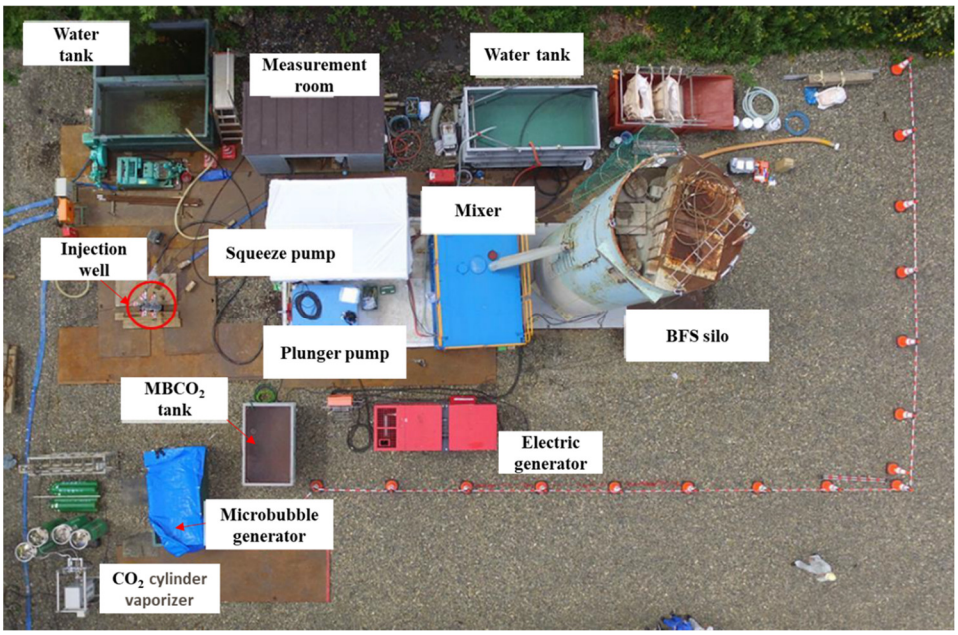


Figure 3. Injection site photograph.

A conceptual diagram of injection test equipment is portrayed in Figure 4. Because different injection materials share one injection well, two injection connecting pipes and corresponding valves for water/$MBCO_2$ and slurry on both sides of the wellhead are used. Using this configuration of the apparatus, slurry and water/$MBCO_2$ can be injected alternately according to the actual circumstances at the site. During and after the injection, the water quality of the river and groundwater near the injection well were analyzed, the carbon dioxide concentration in the injection well was monitored, and the micro-earthquake was monitored using a three-axial geophone. About 75 m^3 of water, 23 m^3 of $MBCO_2$, and 80 m^3 of slurry were injected during the entire injection stage. Findings obtained two months after completion of the injection test indicate that the permeability coefficient decreased greatly compared to that before injection, reflecting the solidification of the slurry in the fracture area of the injection layer.

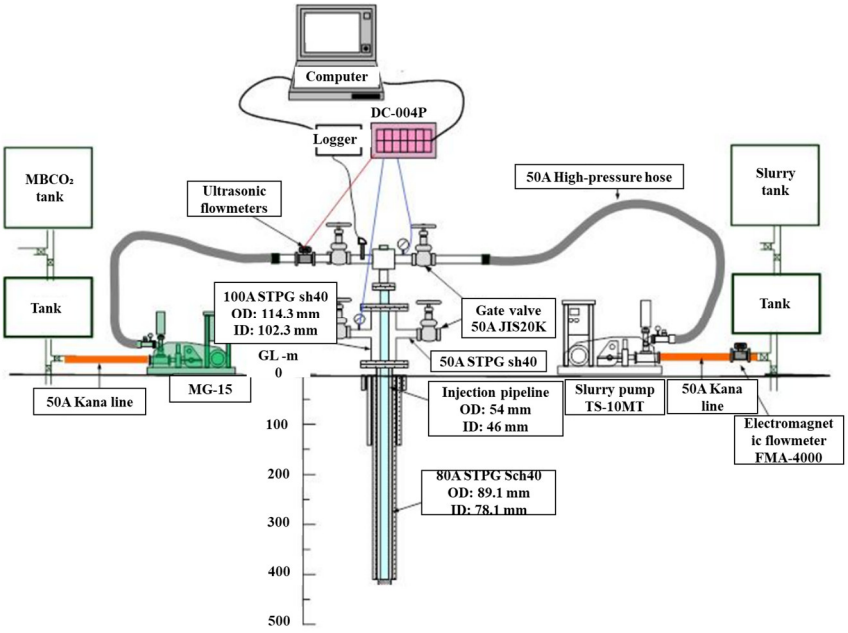


Figure 4. Conceptual diagram of injection test equipment.

5. Discussion

Carbon capture, utilization, and storage (CCUS) is a promising technology for reducing greenhouse gas emissions from power generation and industrial processes. However, there are still significant research gaps and challenges that need to be addressed to enable the widespread deployment of CCUS. One challenge is the cost of CCUS technology, which is currently higher than other forms of decarbonization. The International Energy Agency (IEA) has called for research to develop new materials and optimize capture processes to make the technology more cost-effective [163]. In this regard, research on advanced materials for carbon capture has shown promise in improving capture efficiency and lowering costs [164].

Another challenge is identifying suitable storage sites for carbon dioxide. This requires extensive geologic and engineering analysis to ensure safe and secure storage. Recent research has focused on numerical analysis and the optimization of carbon dioxide storage in saline aquifers with complex geological features [165]. However, there is still a need for further research to identify suitable storage sites and ensure long-term storage integrity.

Scaling up CCUS technology is also a challenge, which requires addressing technical, economic, and regulatory challenges. The Intergovernmental Panel on Climate Change (IPCC) has highlighted the need to address these challenges to enable the large-scale deployment of CCUS [3]. Finally, public acceptance and awareness of CCUS technology is another challenge that needs to be addressed. A survey-based study on public attitudes toward CCUS technology in the United States has shown the need for research to understand public perceptions and develop effective communication strategies [166].

In summary, while CCUS holds great promise for mitigating climate change, there are still significant research gaps and challenges that need to be addressed. These include reducing the cost of CCUS technology, identifying suitable storage sites, scaling up the technology, and addressing public acceptance and awareness. Addressing these challenges requires continued research and innovation to enable widespread deployment of CCUS.

6. Conclusions

This paper presents a discussion of difficulties of greenhouse gas emissions attributable to the use of fossil fuels and the urgent need to reduce their use to constrain global warming. Carbon capture and storage (CCS) and carbon capture, utilization, and storage (CCUS) are garnering large amounts of attention as viable techniques to reduce CO_2 concentrations. This paper specifically examines the latter approach, CCUS, where CO_2 is captured and used rather than only stored. This paper presents analyses of the relevant literature and advancements in different CCUS methodologies, including physical, biological, and chemical storage possibilities. The storage of CO_2 can be accomplished in three main ways: geological storage, ocean storage, and mineral storage. The benefits and shortcomings of each method are discussed, with particular emphasis on mineral storage, where CO_2 is stored in the form of mineral carbonates. Mineral storage is classifiable as direct or indirect carbonation based on the reaction mechanism. Finally, this report introduces a method of simultaneous injection of CO_2 and industrial wastes into an underground goaf for mineralization, which is anticipated as a viable CCUS solution.

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