

A review of CO₂ capture adsorbents: Carbonate/oxide systems and aerogel synthesis

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Abstract

Carbon dioxide (CO₂) emissions have created a global crisis needing to be addressed. Extensive studies have been conducted on reducing these emissions using adsorbent materials with technologies that capture, store, and utilize the CO₂. Elements that exist in nature such as alkali and alkaline earth metals are observed to have favorable properties that lead to high sorption capacities when paired with carbonate and oxide systems. These sorbents have their shortcomings, especially when being regenerated for reuse, which require considerations with improved characteristics. With the capability of having low regeneration temperatures as well as above average CO₂ adsorption capacity, aerogels need to be a strong contender in remedying climate change and global warming through CO₂ capture. This review discusses recent work completed for carbonate and oxide systems, the aerogel synthesis method, and the nanocomposites made with them combined having desirable attributes in capturing CO₂.

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1. Introduction

Our planet is facing an existential crisis. The kind of crisis that may be detrimental to life on earth as we know it. Climate change is this crisis that most of current human existence may never live to fully experience. These forever changing effects should not be something we need to be around to believe it comes to pass. Hoesung Lee, Chair of the Intergovernmental Panel on Climate Change states “Our actions today will shape how people adapt and nature responds to increasing climate risks.” [1]. As we hesitate to act, everything from natural resources to future sustainable development is affected for generations to come. Gambling with the future of humanity by lacking action now is something we cannot afford, especially when we are able to identify some of the contributors that could turn the tide right now.

Of the greenhouse gases responsible for climate change, CO₂ is the major contributor making up over 75% of the global greenhouse gas emissions, with fossil fuels being the greatest [2]. Like the emissions of CO₂ from combustion of fossil fuels in industrial processes, as land use and forestry have contributed to CO₂ emission all directly from human impact. The International Energy Agency stated that global CO₂ emissions had its greatest reduction recorded of 5.2% during the 2020 pandemic followed by the greatest increase of all time reaching a 6% increase pushing an estimated 36.3 gigatonnes (Gt) of CO₂ into the atmosphere [3]. Per the UN Paris Agreement, the one of the key objectives is “to limit the global temperature increase in this century to 2 °C while pursuing efforts to limit the increase even further to 1.5 degrees.” [4].

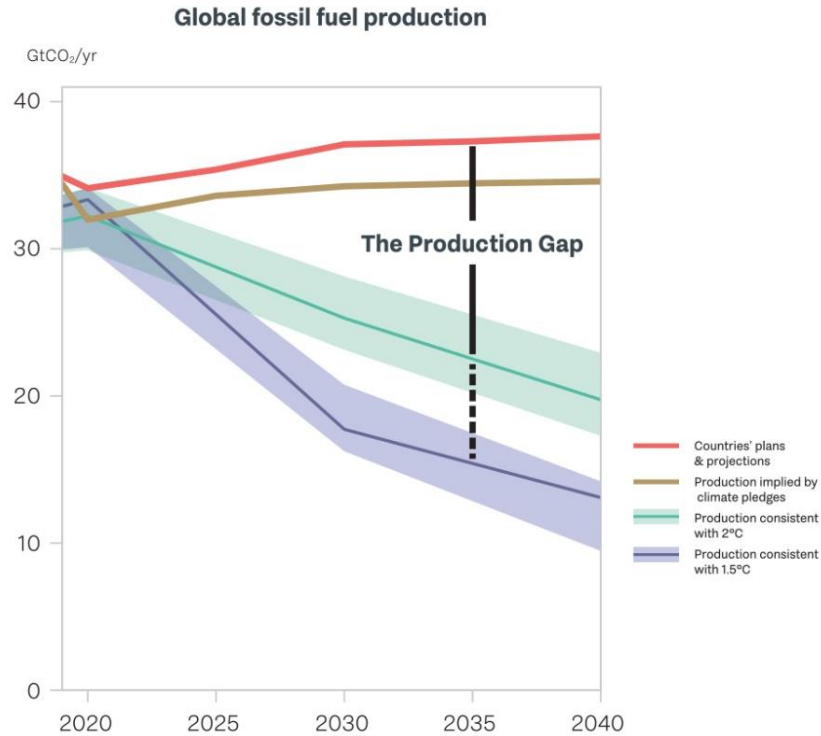


Figure 1. Production gap of global fossil fuel production [5]

Visible in Figure 1, the production gap report of 2021 for global fossil fuel production shows a rather large gap of meeting the committed goal of limiting global warming to 1.5 °C [5]. To your average person, these numbers may not mean much, and some may argue that the planet has faced this through its billions of years of existence. The Industrial Revolution created an undoubtedly significant effect on the earth’s climate due to human activity. With industrial processes increasing, the output of greenhouse gases over the years has taken effect and observations need only be made to find the common culprit.

Global climate change article written by NASA states “effects that scientists had long predicted would result from global climate change are now occurring, such as sea ice loss, accelerated sea level rise, and longer, more intense heat waves.” [6]. These are examples of weather and environmental effects derived from climate change. Agriculture is affected as well,

making farming crops more difficult because of droughts and flooding. This also affects soil quality creating food shortages. Livestock livelihood is affected with situations like in the summer of 2022 where thousands of cattle in Kansas perished due to extreme heat and humidity. Not only does climate change affect a variety of animals and their habitats, but as the examples stack up, the reality of humanity being affected should weigh on a conscious mind. Everything from deteriorating air quality with increased wildfires and ozone smog to people being economically impacted through displacement because of extreme weather patterns developing and causing destruction [7]. The difference of human influence compared to natural influence on global temperature (Figure 2) is staggering and is accelerating as decades pass due to human involvement.

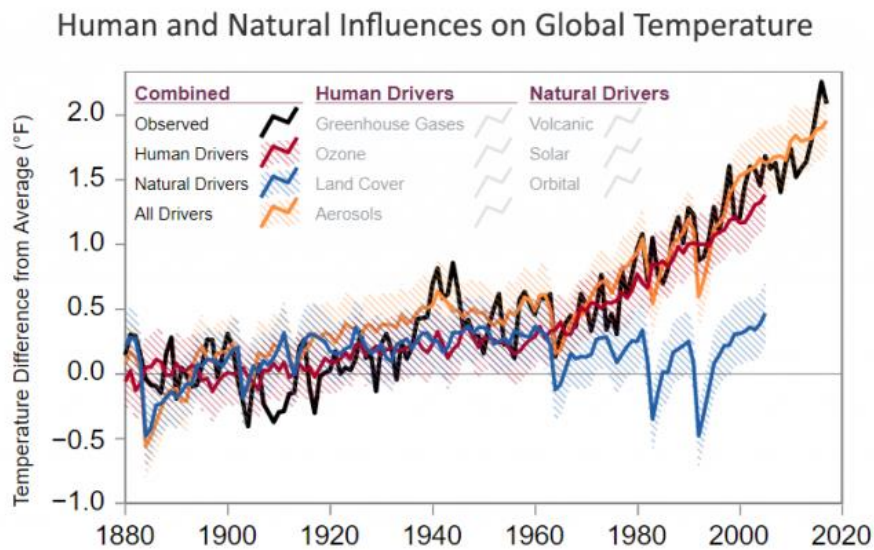


Figure 2. Influences on Global Temperature from Natural and Human Drivers

Source: U.S. Global Change Research Program, Fourth National Climate Assessment, [Chapter 2: Our Changing Climate](#), 2017.

Solutions are present in mitigating climate change using renewable energy and sustainable technology. Carbon capture, utilization, and storage (CCUS) is an approach taken by many researchers to offset climate change. Different industries need tailored separation technologies that will adapt to the overall process conditions with approaching the same goal of CCUS. The main advantages and disadvantages of each of these technologies are discussed below in Table 1.

Method	Advantages	Disadvantages/Challenges
Physical absorption	<ul style="list-style-type: none"> ✓ >90% CO₂ separation efficiency. ✓ Low energy consumption for sorbent regeneration. ✓ Temperature required for the process is lower than for chemical methods. ✓ Low corrosivity and toxicity. ✓ More economical at a higher partial pressure of CO₂. 	<ul style="list-style-type: none"> ➤ Low effectiveness of CO₂ capture. ➤ Low selectivity towards CO₂. ➤ Limitation on operating temperature (the capacity of solvents is best at low temperatures). ➤ High capital and operational costs. ➤ Economically unprofitable if CO₂ partial pressure <15% vol.
Chemical absorption	<ul style="list-style-type: none"> ✓ Most mature technology. ✓ Simplicity and the possibility of using it with a low partial pressure of CO₂. ✓ Suitable for retrofit. ✓ High absorption capacities. ✓ Product purity >99% vol. 	<ul style="list-style-type: none"> ➤ Need to clean the exhaust gases (water, SO_x, NO_x). ➤ Corrosivity of proces apparatus. ➤ High energy demand for regenerating the solvent. ➤ Solvent toxicity and loss ➤ Large absorber volume. ➤ Environmental impacts due to solvent degradation.
Membranes	<ul style="list-style-type: none"> ✓ >80% CO₂ separation efficiency. ✓ Uncomplicated process. 	<ul style="list-style-type: none"> ➤ Strength problems at high pressures. ➤ Strict temperature requirements.

Method	Advantages	Disadvantages/Challenges
	<ul style="list-style-type: none"> ✓ No regeneration energy is required. ✓ Simple modular system. ✓ No waste streams. ✓ Higher separation energy efficiency compared to absorption and adsorption. ✓ No additional chemicals in separation process. 	<ul style="list-style-type: none"> ➤ Plugging by impurities in gas stream. ➤ Sensitivity to corrosive gases. ➤ Need for gas compression. ➤ Difficult to maintain performance over long-term operation. ➤ Preventing wetting is a major challenge. ➤ Permeation and selectivity issues.
Calcium looping (CaL)	<ul style="list-style-type: none"> ✓ Cheap raw materials for sorbents synthesis. ✓ Optimal method for retrofit of pulverized coal-fired power plants, sorption-enhanced hydrogen production process or BECCS. 	<ul style="list-style-type: none"> ➤ Reduced CO₂ uptake due to sintering of sorbents in many cycles. ➤ Additional expenses regarding fast rapid degradation of sorbent. ➤ Waste management of sorbents.
Cryogenic method	<ul style="list-style-type: none"> ✓ High CO₂ purity. ✓ High separation efficiency (up to 99.9% vol. CO₂). ✓ Production of ready to transport, pure liquid CO₂. ✓ No need of chemical reagents. ✓ Suitable for high pressure gas stream with high concentration(>50% vol.). ✓ Easy scaled-up to industrial application. 	<ul style="list-style-type: none"> ➤ Significant energy penalty due to refrigeration (low temperature, high pressure condition). ➤ The energy consumption to minimize the moisture level in the flue gas stream (preventing ice formation and blocking the process. equipment). ➤ High capital costs.

Method	Advantages	Disadvantages/Challenges
Chemical looping combustion (CLC)	<ul style="list-style-type: none"> ✓ Simplicity and the possibility of using it with a low partial pressure of CO₂. ✓ The exhaust gas from the air reactor is mainly N₂. ✓ The exhaust gas stream from the fuel reactor is composed of CO₂ and H₂O (CO₂ can be easily separated by a condenser). ✓ Avoids huge energy penalty and thus less operational cost. 	<ul style="list-style-type: none"> ➤ Insufficient stability of the oxygen carrier. ➤ Slow redox kinetics. ➤ Process is still under development and not implemented in industry scale.
Adsorption	<ul style="list-style-type: none"> ✓ >85% CO₂ separation efficiency. ✓ Ease of use and maintainability of the installation. ✓ Since adsorbents can be reused, low waste generation. ✓ Reversible process (physical adsorption). ✓ Large selection of materials with high CO₂ uptake. ✓ Low energy requirement to regenerate an adsorbent material. ✓ Wide operability range. ✓ Possibility to use waste biomass or industrial residues as raw materials do adsorbent synthesis. 	<ul style="list-style-type: none"> ➤ Low CO₂ selectivity. ➤ Lower CO₂ uptake compared to other separation technologies, such as absorption or cryogenics. ➤ Lack of expertise. ➤ Scalability. ➤ Problem with the resistance to high temperature. ➤ Continuous, low-cost manufacture on a widespread scale of an adsorbent. ➤ Sensitivity to sulfur/nitrogen oxide and moisture. ➤ Poor durability of adsorbents (additional cost of material replacement).

Table 1. CO₂ separation techniques with their positive and negative points [67]

Physical and chemical absorption have been studied extensively with their high separation efficiency and great absorption capacity. However, they would not be considered a cost-effective option and either being low in CO₂ selectivity or suffering from degradation keeps these as less

than desirable as a long-term separation method. The same goes for membranes when it comes to degradation and the cryogenic method being costly. The looping techniques provide an alternative that may be adaptable to specific industries given certain conditions. The adsorption technique has widespread capabilities to offer with relatively high separation efficiency, abundance of adsorbents for CO₂ capture, great regeneration ability, and can be used at many temperatures [67]. These are undeniably some of the most sought-after traits needed for the ideal CO₂ separation technology which, unlike the absorption and cryogenic methods, have little research available in comparison leaving investigations required to determine their full potential.

These novelty tactics will help ensure that the agreed upon global temperature regulation per the UN Paris Agreement become achievable. Of these novelty tactics, this report will investigate different CO₂ capture mechanisms and a synthesis method.

More specifically,

- Capture sorbents and carbonate/oxide systems as CO₂ capture mechanisms.
- The aerogel synthesis method.
- Characterization techniques used in determining their capture and storage capability.
- Future observations on adsorbents discussed.

Following the introduction, the review of the literature is covered in section 1. The characterization techniques will be examined in section 2, and the discussion and conclusion given in section 3.

2. Review of the Literature

2.1. Capture sorbents

“Adsorption is a process in which components in liquids, gases or dissolved substances are held by weak van der Waals interactions in the solid surface.” [33]. Figure 3 illustrates when an adsorbate attaches to the surface of an adsorbent dependent on the intermolecular forces at work.

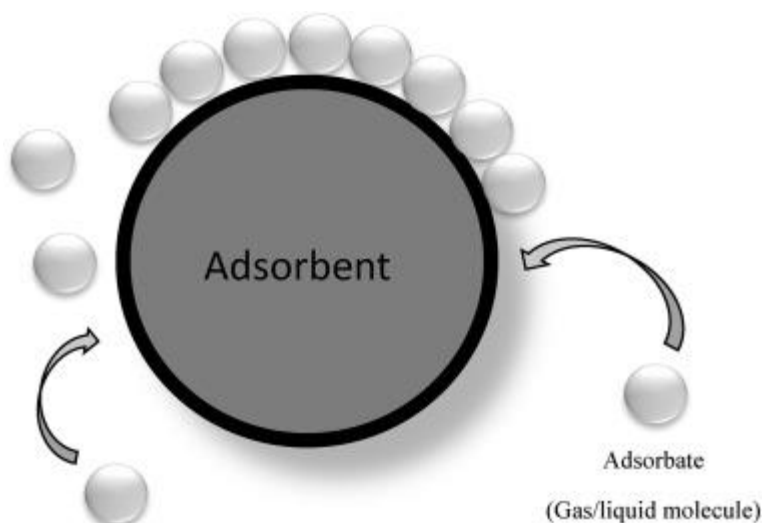


Figure 3. Process of adsorption [42]

Physisorption occurs when CO₂ can be captured by the adsorbent due to the van der Waals forces. It is most suitable in controlling selectivity, but has low CO₂ capacity, which take place during molecular sieving and include compounds like zeolites, metal organic frameworks (MOFs), and mesoporous silica [33,64]. Chemisorption transpires when CO₂ and adsorbent surface sites chemically bond to adsorbents like metal oxides and carbon. Chemisorption typically takes place at higher temperatures compared to physisorption because the activation

energy is larger [65]. Table 2 provided below briefly discusses the advantages and disadvantages of the use of various solid adsorbents for CO₂ separation [59].

Adsorbent type	Advantages	Disadvantages
Metal Oxide	<ul style="list-style-type: none"> • Abundant availability [19,23] • Low toxicity [19] • Cost-effective material [19] • Adsorption abilities over a wide range of temperature and pressure conditions [27] 	<ul style="list-style-type: none"> • High regeneration energy requirements [28]
Zeolite	<ul style="list-style-type: none"> • Good cyclic and mechanical stability [12] • High thermal stability [29] • High surface area [29] 	<ul style="list-style-type: none"> • Low CO₂ selectivity [12,13,16] • Low adsorption uptake [16,17] • High regeneration energy requirements [16] • High cost of materials [12]
MOFs	<ul style="list-style-type: none"> • High surface area [16,17,18] • Controllable pore structures [12,16,18] • High physicochemical stability [17] • Adjustable chemical functionality [12] 	<ul style="list-style-type: none"> • Low CO₂ selectivity [12,16,17] • Low adsorption uptake in the presence of impurities [12,16] • High cost of materials [12] • Inability to retain the structure during removal of solvent [18]
Silica	<ul style="list-style-type: none"> • High surface area [12,16] • Tuneable porous structure [12,16] 	<ul style="list-style-type: none"> • Low adsorption capacity under ambient conditions [16]

Adsorbent type	Advantages	Disadvantages
Carbon	<ul style="list-style-type: none"> • Good thermal and mechanical strength [12,16,17] 	<ul style="list-style-type: none"> • High energy consumption during regeneration [17]
	<ul style="list-style-type: none"> • Wide availability [16] 	
	<ul style="list-style-type: none"> • Low cost [12,16,17] 	<ul style="list-style-type: none"> • Their application is limited to high pressure gases [16]
	<ul style="list-style-type: none"> • High degree of surface reactivity [30] 	<ul style="list-style-type: none"> • Low sensitivity to moisture and impurities [12,13,16]
	<ul style="list-style-type: none"> • High thermal stability [12,16] 	
	<ul style="list-style-type: none"> • Less energy consumption during regeneration [17] 	
	<ul style="list-style-type: none"> • Thermal/chemically stable [17] 	

Table 2. Strength and weaknesses of different solid adsorbents [59]

Another process is when CO₂ is used as the reactant which is known as carbonation. As the diffusion of CO₂ particles deposit on the surface of any alkali-metal oxide or alkaline earth metal oxide, the bulk forms stable carbonate molecules affecting CO₂ capture efficiency. Figure 4 shows how physisorption, chemisorption, and bulk carbonation differ from one another. Chemisorption and carbonation are the mechanisms that directly relate to carbonate and oxide systems used in adsorption.

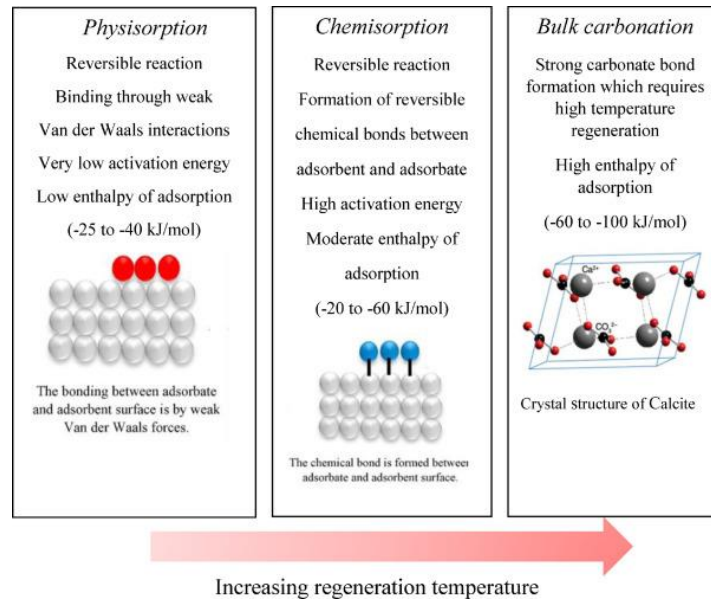


Figure 4. Characteristics of different mechanisms for adsorption [33]

2.2. Carbonate/oxide systems

A carbonate can be classified as a compound derived from carbonic acid or CO_2 [8]. Carbonates have produced large quantities of chalk, limestones, and marbles over time which account for the largest reservoir of carbon on earth [9][10]. These solid adsorbents (or sorbents) have been studied like others with similar properties to determine the reaction with CO_2 by either adsorption to sorbent surface, mineralization forming an insoluble carbonate, membrane separation via diffusion, or controlled diffusion via molecular sieving [10]. This review will be based on the capture sorbents and carbonate oxide systems used in CO_2 capture.

During carbon mineralization, CO_2 converts to solid inorganic carbonates creating these carbonate deposits [11]. The natural process of carbonization does sequester CO_2 permanently, but sequestration occurs at an extremely slow rate and any methods of aiding the rate of storage may end up producing greater amounts of carbon [12]. Injecting CO_2 into carbonate reservoirs

below the sea floor [14] may be viable pending a life cycle analysis. “The Department of Energy estimates that storage capacity along the U.S. Gulf Coast is enough to hold 500 billion metric tons of CO₂ – more than 130 years of the country’s total industrial and power generation emissions, based on 2018 data.” [15]. Figure 5 demonstrates the idea behind carbon sequestration on this level.

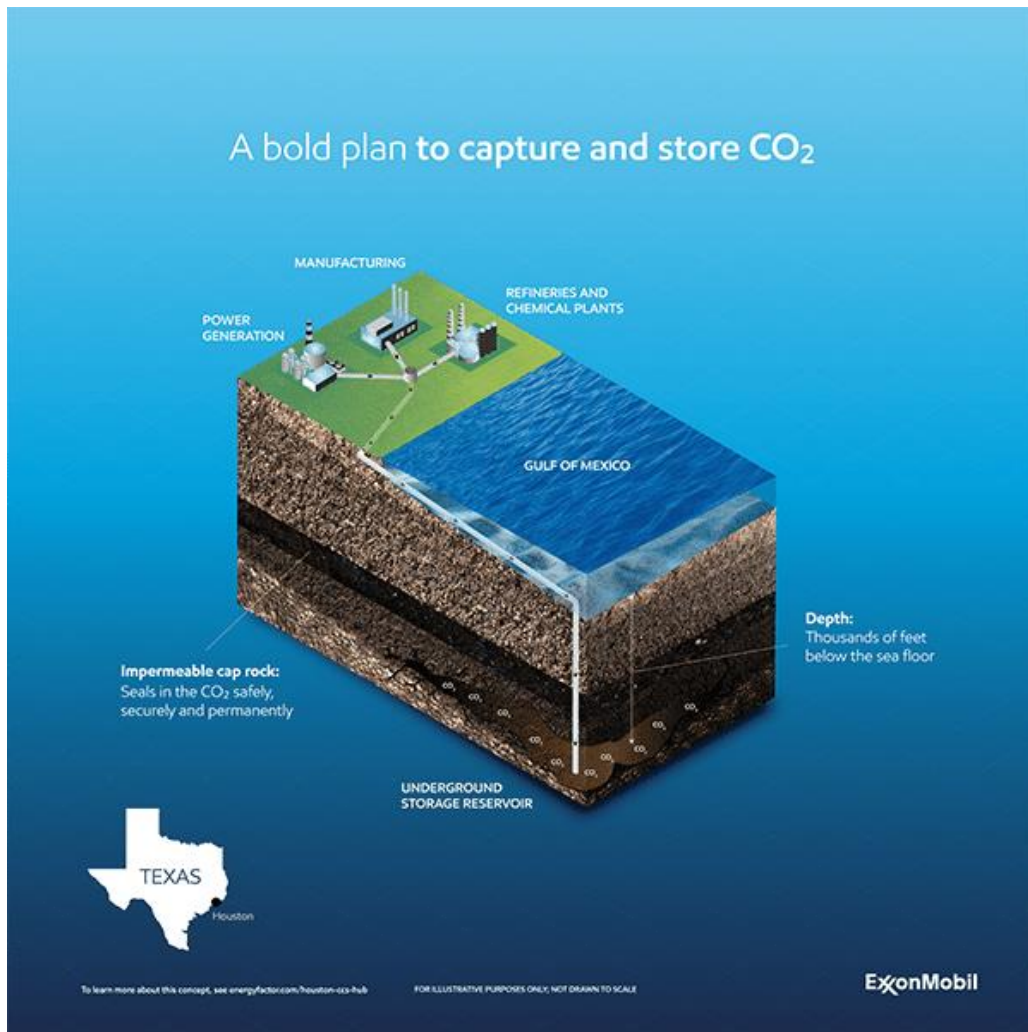


Figure 5. Illustration of proposed method of CO₂ capture in the Gulf of Mexico [15]

Carbon mineralization also has two processes where it can occur in situ, where industrial processes are captured, compressed, and stored to produce solid carbonates, or ex situ, where

CO₂ is engineered via mineralization to produce solid carbonates [13,62]. Both options provide benefits that would prove useful in increasing sequestration and the possibility of utilization. An alternative, molten salts have become a more attractive candidate to serve as media in CO₂ capture because they are found to be less toxic, less corrosive, and affordable compared to other solvent-based media used currently [17]. What seems to be most desirable is that molten salt can stimulate a variety of sorbents, have ideal CO₂ absorption capability, and the ability to absorb quickly [17-21]. A fuel cell option that has been developed by FuelCell Energy uses molten carbonate electrolytes to capture CO₂ from flue gas while simultaneously generating electricity from natural gas, coal, and other fuels. A modeled 550-megawatt (MW) coal-fired power plant using this molten carbonate fuel cell with an additional stream of natural gas captured 90% of the CO₂ emissions including the production of 351 MW of power [16]. Figure 6 displays how this molten carbonate fuel cell would work in converting flue gas to energy.

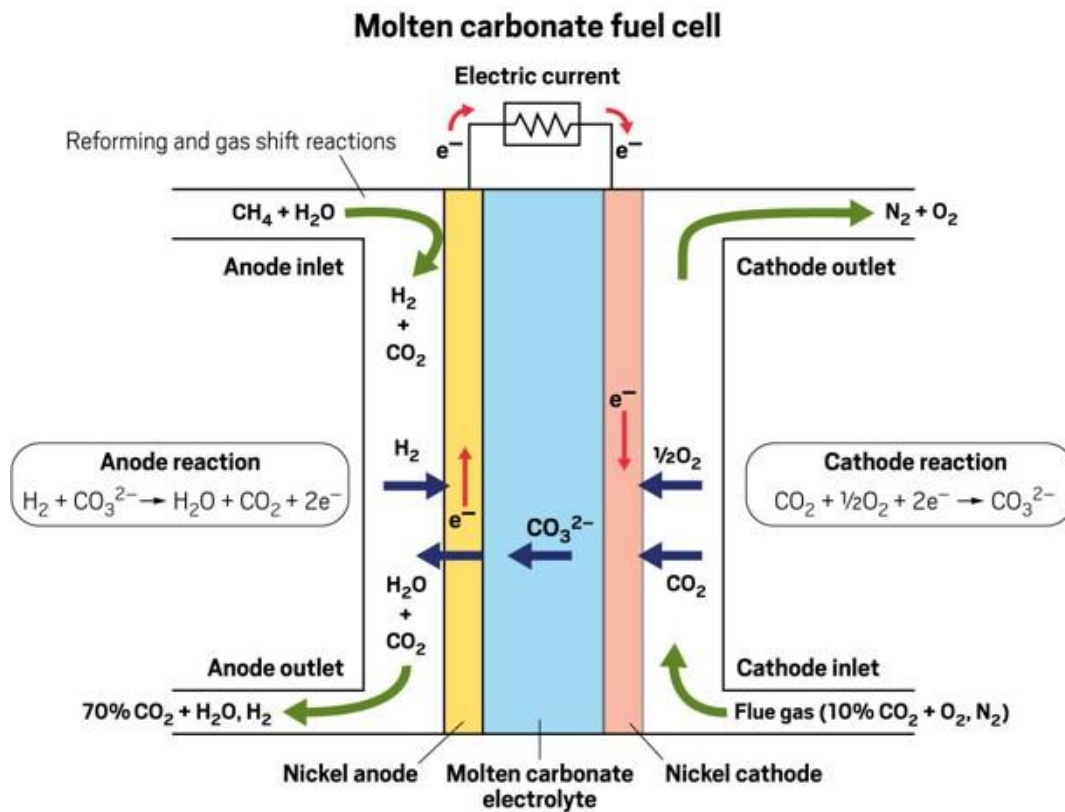


Figure 6. FuelCell's molten carbonate energy fuel cell [16]. Credit: Adapted from *Int. J. Hydrogen Energy/IEA*

Not only have molten salts proven to have outstanding CO₂ capture ability, but alkali metals and alkaline earth metal carbonates promoted metal oxide-based adsorbents demonstrated even greater ability [22].

Group 1 alkali-metal oxides, typically lithium oxide (Li₂O) and sodium oxide (Na₂O), have been observed for their ability to adsorb CO₂. Li₂O has yet to be proven on its regenerative ability and is far more expensive than other oxides used in CO₂ capture. With alumina having relatively low sorption capacity, Na₂O has shown good success in promoting alumina to capture CO₂ via chemisorption [23-25]. Similarly, alkali-metal carbonates have shown great capacity of CO₂ adsorption, proven physisorption occurs around 50-80 °C, desorption occurs at 200 °C, and be a cost-effective compound in CO₂ capture [22]. Flue gas in industrial processes are treated using these alkali-metal carbonate-based adsorbents to capture CO₂ as well [26-33]. With flue gases directly causing between 10-15% of CO₂ emissions [34-36] at higher temperatures, CO₂ capture research is necessary and would see a great impact on finding cheap and effective adsorbents. Group 2 oxides have proven to be among the most cost-effective, simple to produce in large quantities, and have the widest availability of all CO₂ capturing materials.

Of the group 2 oxides, magnesium oxide (MgO) and calcium oxide (CaO) have been extensively studied for their adsorptive properties. MgO temperature of adsorption and desorption being lower than that of CaO, but CaO have a higher adsorption capacity. The theoretical uptake capacity of MgO is 24.8 mmol/g of CO₂, making it a desirable adsorbent for CO₂ capture in the range of 200-400 °C [58]. The biggest negatives on pure MgO are the slow kinetic reactivity which, even having high theoretical uptake, results in low uptake, although

having favorable adsorption capacity and the lack of thermal stability during regeneration [22,37,38]. This also explains the absorption and adsorption model of MgO reacting with CO₂ in the presence of water [66]. Figure 7 illustrates the Mg molecules inhibited by the growing layer of MgCO₃ due to slow kinetic reactivity.

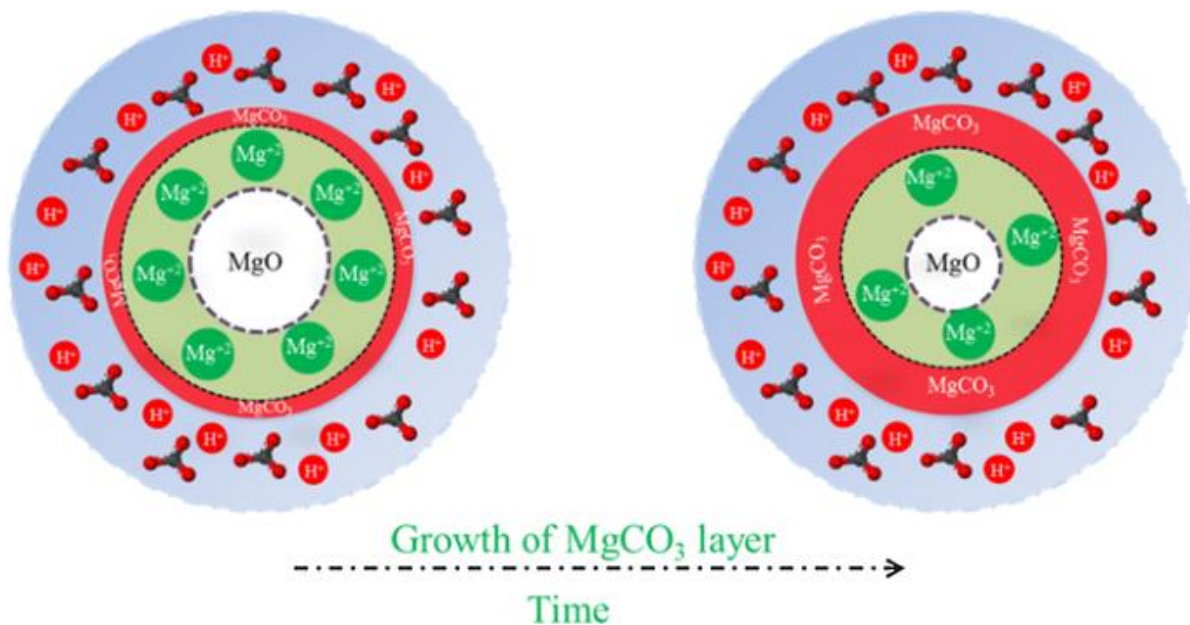


Figure 7. MgO-CO₂-H₂O adsorption and absorption model [66]

Modifying MgO to be mesoporous or creating molten salt promoted MgO have resolved issues previously discussed with pure MgO [22,25]. CaO have a high capacity of CO₂ adsorption at high temperatures (>600 °C) and desorption occurring at even higher temperatures (>700 °C). The most observed issue with CaO is the sorption capacity greatly decreases after several cycles of regeneration due to sintering [17,33,39-41,63]. The addition of supporting minerals like alumina can make CaO a strong contender in being a sustainable adsorbent for CO₂ uptake [22].

2.3. Aerogel synthesis method

Aerogels are formed using a solvent and a polymer to form gel, which then the liquid contained in the gel is replaced by air [43]. These can be created using a variety of methods and techniques. These primarily silica-based aerogels have great properties in being a CO₂ sorbent, with the capability of being enhanced to improve CO₂ selectivity [45-48].

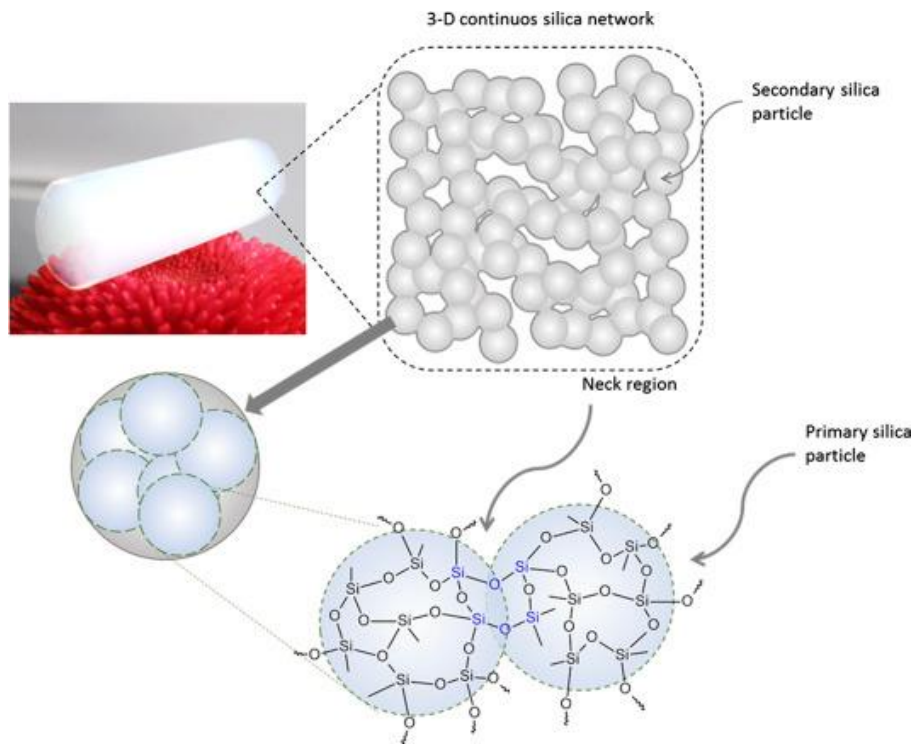


Figure 8. Silica aerogel monolith with silica particle network [47]

Figure 8 is an example of a silica aerogel and its network of particles. They have been characterized to have sorption performance of 4.43 and 3.57 mmol/g when it came to CO₂ capture capacities for humid and dry air, respectively [48,60]. Also, being mesoporous, having large specific surface area, and are low in density are exactly why aerogels are considered

excellent insulators and a part of the lightest solids ever created [43]. Table 3 discusses some of the positives and negatives associated with the different aerogel structures.

S.No	Synthetic method	Advantages	Disadvantages	Aerogels synthesized
1	Sol–Gel	Simple and widely studied	Aerogels are amorphous	Inorganic oxide aerogels, carbon aerogels and composite aerogels
		Monoliths can be obtained	Hydrolysis and condensation are very fast	
			Time consuming	
2	Epoxide addition	Hydrolysis and condensation can be controlled	Aerogels obtained are amorphous	ZnO, Fe ₂ O ₃ , Cr ₂ O ₃ , CO ₃ O ₄ , Gd ₂ O ₃ , Ta ₂ O ₅
		The properties of the final aerogel can be tailored based on the necessity	Time consuming	
2	Self assembly	Large and complex structures can be obtained	Difficult to control the assembly of building blocks	Chalcogenide, Carbonitride, Inorganic oxide aerogels, Metallic aerogels
		Crystalline aerogels are obtained		
3	Template	Highly crystalline aerogels are obtained	Removal of templates are difficult and damages the aerogel network	Functional aerogels
		Assembly of building blocks can be controlled		
4	Emulsion	Aerogels can be obtained in micro spherical and other forms	Difficult to remove the emulsifier	Polymeric and inorganic oxide aerogels
5	3-D Printing	Hybrid and modern technique	High cost	Polymeric and composite aerogels

S.No	Synthetic method	Advantages	Disadvantages	Aerogels synthesized
		Diverse nanostructures can be fabricated	Viscosity of the solution needs to be maintained	
			Rheology of the material is crucial	

Table 3. The pros and cons of various aerogel syntheses [44]

The original technique used in creating aerogel is known as the sol-gel technique [44-48]. This technique involves sol-gel precursors that undergo hydrolysis and condensation creating a colloidal suspension of solid particles known as sol [44]. Once these nanoparticles have developed all around the solution, the pores are then saturated with a liquid resulting in a gel. Figure 9 demonstrates this sol-gel process of how the synthesis takes place. The final step of creating the aerogel (d) identified in the figure is accomplished by a process known as supercritical drying.

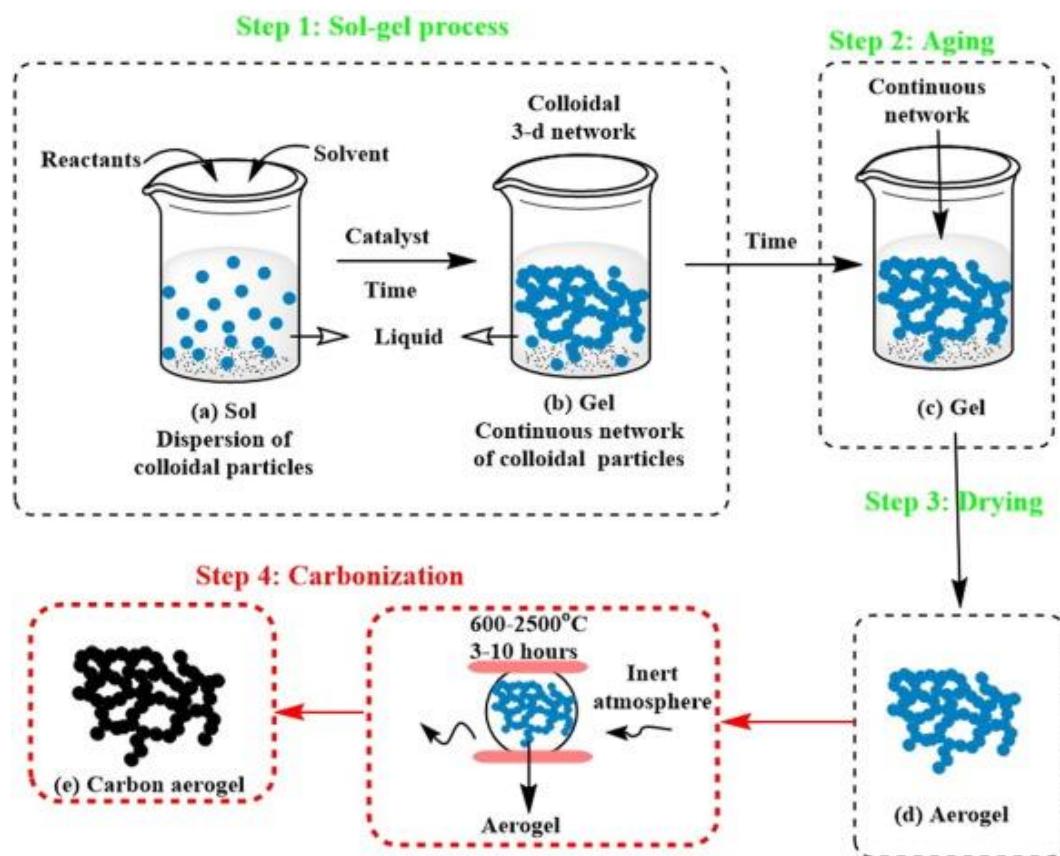


Figure 9. Synthesis of aerogel via sol-gel method with additional step solely for carbon-based aerogels [46]

Proper drying is crucial in determining the pore structure of the aerogel because of induced reduction from capillary pressure [45]. Supercritical drying involves removing the liquid from the pores by filling with a liquid solvent, CO₂ has favorable properties making it most used [47], above the supercritical point, where it can exist as a gas or a liquid, then vented to atmosphere and repeated for formation of aerogel [44-47]. Figure 10 shows a temperature versus pressure – axis the different drying techniques possible in creating aerogel.

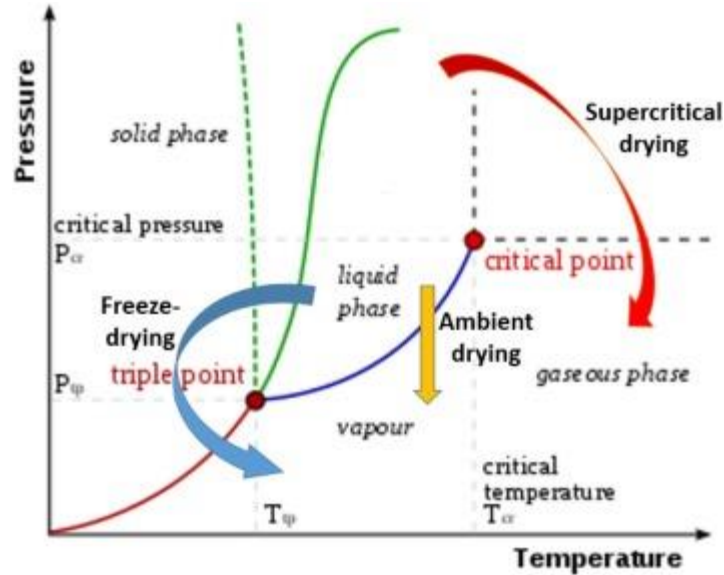


Figure 10. Different phases and routes for aerogel drying techniques [45]

The other well-known drying techniques of freeze-drying and ambient drying did not produce the CO_2 adsorption ability as the supercritical dried aerogel [45,46]. Following the completion of the drying technique to obtain the aerogel, step 4 of Figure 9 shows an additional step of carbonization. This process includes calcination of the aerogel to a temperature of over $600\text{ }^\circ\text{C}$ in an inert atmosphere [45]. Extensive review on the most common and original aerogel method, oxide aerogels, have been studied providing a plethora of data on their CO_2 capture abilities and applications [48]. Instead, observations on aerogels that pertain to carbonates and oxide systems will be discussed.

Carbon aerogels are formed from organic molecule precursors when the elevated temperatures used in calcination then decompose and convert the organics contained in the gel via pyrolysis [45]. A study observed the temperature used in pyrolysis would affect the capacity for CO_2 capture by either increasing or decreasing the activated carbon aerogel effectively reducing or enhancing total pore volume and specific surface area [49]. Using potassium carbonate (K_2CO_3) and carbon aerogel nanocomposite, Yang *et al.* studied the regeneration

temperature of the carbon aerogel – K_2CO_3 nanocomposite where nanocrystals had formed in the mesopores of the carbon aerogel as a viable candidate for CO_2 from flue gas [50]. The study concluded that of the nanocomposites created via wet impregnation of K_2CO_3 in the nanopores of carbon aerogel with the pore width of 7 nanometers, showed the lowest desorption temperature and demonstrated the highest CO_2 capture capacity of 13.0 mmol/g under moist conditions. Information provided by another group showed that this outperformed the theoretical K_2CO_3 sorption capacity alone [51].

Aerogels that not only possess organic materials, but inorganic as well form a hybrid aerogel by a variety of electromagnetic forces at work [61]. Adding such properties that organic-inorganic composites provide has proven to create more mechanical stability compared to conventional aerogels [47]. S.J. Han *et al.* used different molar ratios of Mg/Al to produce mesoporous MgO – Al_2O_3 aerogel adsorbents with the goal of determining the best CO_2 adsorption capability at a temperature of 200 °C of flue gas. [52]. Studying the different physiochemical properties and CO_2 capture capacity of these adsorbents, the prepared 0.5 Mg/Al molar ratio contained the best medium basicity, which equated to the best CO_2 capturing performance for the flue gas. Being able to determine characteristics like these are crucial and are done using various instrumentation.

3. Characterization

3.1. CO₂ sorption capacity

A key characterization technique that is used by researchers and most important is an experimental set up that can output adsorption capacities at different temperatures per time [48]. This design provides a measurement that could provide operational data capable of determining system error [53]. The CO₂ adsorption capacity calculated is typically trying to emulate flue gas at certain conditions, if possible. The following equation shows how that calculation is acquired:

$$\begin{aligned} & \text{CO}_2 \text{ adsorption capacity (wt\%)} \\ &= \int \frac{(C_{in} \times F_{in} - C_{out} \times F_{out}) \times MW_{CO_2}}{m_{ads}} dt \times 100 \end{aligned} \quad [52,53]$$

C_{in} and C_{out} : influent and effluent CO₂ concentrations

F_{in} and F_{out} : total flow rate at the inlet and outlet of the adsorption column

MW_{CO_2} : molecular weight of CO₂

M_{ads} : amount of adsorbent

Figure 11 shows an image of what the typical set up looks like for CO₂ absorption experiments.

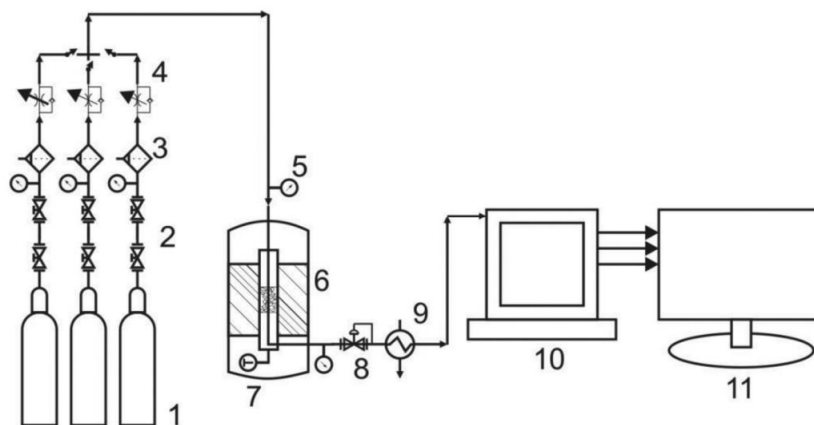


Figure 11. Schematic of system used in CO₂ absorption experiments. 1. Cylinders; 2. Two-stage pressure regulators; 3. Gas filter system; 4. Differential flow controllers; 5. Pressure sensor; 6. Reactor bed; 7. Electric furnace; 8. Back-pressure regulator; 9. Heat exchanger; 10. Gas chromatograph; 11. Computer. [53]

Another, more well-known, method for characterizing CO₂ capture is done by examining the surface area.

3.2. BET model

The Brunauer – Emmett – Teller (BET) model is the most widely used in determination of surface area for porous materials. These adsorbents have their surface area calculated through isotherms that examine nitrogen adsorption and desorption. The interactions between the adsorbents and nitrogen can correctly provide measurements for specific surface area to $0.01 \text{ m}^2\text{g}^{-1}$ and pore sizing diameter from 0.3 to 100 nm [45,54]. The adsorption isotherms in Figure 12 shows the various carbon aerogel - K₂CO₃ nanocomposites which were compared to adsorption isotherms of carbon aerogels prior to K₂CO₃ impregnation. Measured at 77K, the isotherms indicated there are mesopores as well as micropores found in the nanocomposites. The various pore sizes demonstrated good ability to capture CO₂ as well as H₂O capture at a rapid rate proving significant CO₂ adsorption is possible [50]. The decreased nitrogen adsorption also proved the success of K₂CO₃ impregnation when compared to the carbon aerogel isotherms.

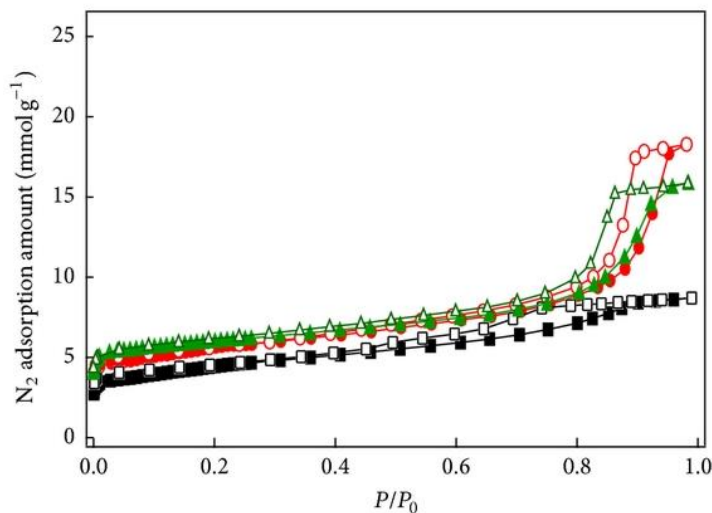


Figure 12. Nitrogen adsorption isotherms of carbon aerogel - K_2CO_3 nanocomposites. Pore width: black 7 nm; green 16 nm; red 18 nm. [50]

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3.3. Thermogravimetric analysis

A thermal analysis technique that can analyze the thermal properties and stability of a compound by simply measuring the weight change and observing the reactions. Thermal gravimetric analysis (TGA) provides the prediction of thermal stability for samples, as well as allowing kinetics of chemical reactions to be studied under various circumstances [54]. It has many applications in characterizing physiochemical changes of materials using regulated temperature which works well with observing these adsorbents under a nitrogen atmosphere [55]. Figure 13 shows how these various carbon aerogel - K_2CO_3 nanocomposites were regenerated by heating up to 473K in an inert atmosphere. The thermal decomposition shows two weight losses, first being desorption of water followed by potassium bicarbonate decomposing to potassium carbonate. Potassium bicarbonate to potassium carbonate is where water and CO_2 are desorbing from their respective nanocomposite. The blue line in Figure 13 is

bulk potassium bicarbonate, which only displayed decomposition at a high temperature, where the various carbon aerogel - K_2CO_3 nanocomposites showed decomposition beginning to occur at lower temperatures. For their research, the carbon aerogel - K_2CO_3 nanocomposites exhibited high reactivity which ultimately result in their regeneration at lower temperatures [50].

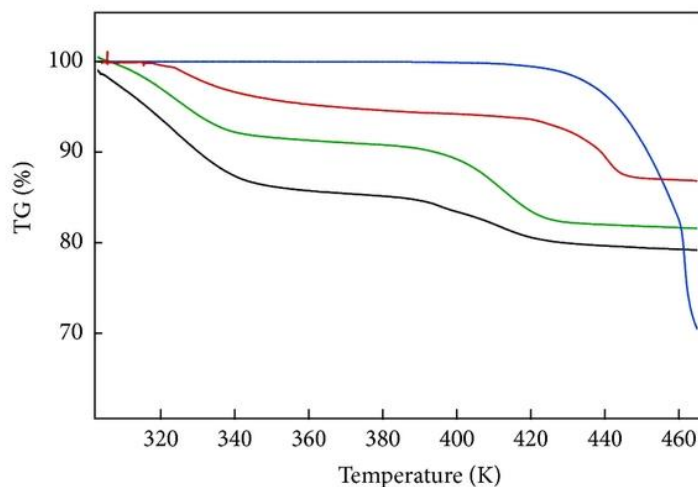


Figure 13. Thermogravimetric curves of carbon aerogel - K_2CO_3 nanocomposites. Blue: $KHCO_3$, black: 7 nm pore width carbon aerogel - K_2CO_3 ; green 16 nm pore width carbon aerogel - K_2CO_3 ; red 18 nm pore width carbon aerogel - K_2CO_3 . [50]

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3.4. X-ray diffraction

X-ray diffraction (XRD) is an important method that will provide chemical composition and structure data of adsorbents. The visual aid through the diffractogram will illustrate the success of synthesis compared the normal peaks of a compound to a standard [56]. The crystallinity will reflect peak intensity [57] as it will be greatly beneficial when using this method to provide data on any alkali or alkaline earth metal oxides as well as the formation of hybrid aerogel composites. Under moist conditions, Figure 14 displays the various pore

width carbon aerogel - K_2CO_3 nanocomposites after CO_2 capture. The presence of potassium bicarbonate is identified as the main diffraction peaks per nanocomposite when the mesopores of the carbon aerogel were impregnated using K_2CO_3 . $K_4H_2(CO_3)_3 \cdot 1.5H_2O$ is also observed in the 16-nanometer and 18-nanometer composites, but the 7-nanometer composite only contained $KHCO_3$ peaks [50]. A histogram of these various carbon aerogel - K_2CO_3 nanocomposites after regeneration provided good detail that complete regeneration occurred when peaks were compared.

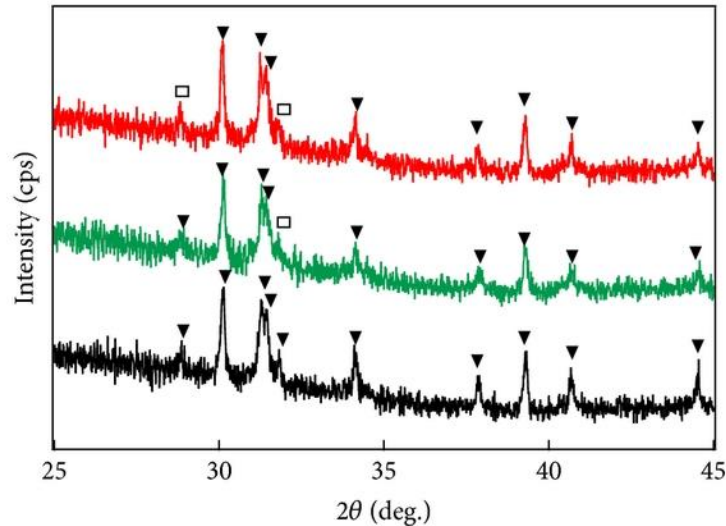


Figure 14. Histogram of carbon aerogel - K_2CO_3 nanocomposites following CO_2 capture in moist conditions. Pore width: black 7 nm; green 16 nm; red 18 nm. [50]

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4. Discussion and Conclusion

The ideal CO₂ adsorbent will be cost-effective, have low heat capacity, rapid kinetics, high CO₂ adsorption capacity, high CO₂ selectivity, and favorable physical and chemical properties that is stable when cycled repeatedly [45]. With irreversible climate change and global warming rising, the time for action is now. Certain alkali metals and alkaline earth metals combining to create carbonates and oxides have been researched sufficiently proving consistent and reliable sorption capacity. Although some natural sorbents are abundant in quantity, quality adsorption still needs to be developed by providing reusable alternatives that do not have rapid reduction after continued use.

Aerogels may be the way forward with a large assortment of synthesis methods, great sorbent materials, and a high sorption capacity that has been observed having advantageous capability of regeneration [45]. To the best of my knowledge, research surrounding carbonate and oxide systems combined with aerogels have few recent studies which have not been exhausted although being proven to exhibit exceptional CO₂ capture capacity and have a considerably low sorbent regeneration temperatures [50]. Low density, high porosity, large specific surface area, and ability to be created from many compounds forming hybrid aerogels with high CO₂ selectivity [47] are exactly why further investigations on aerogel optimization are necessary to manufacture these sorbents commercially.

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List of Terms

Greenhouse gases – harmful gases that create a barrier, trapping outgoing energy and heat from leaving Earth’s atmosphere.

Gigatonne (or gigaton) – one billion tonnes, typically used in describing carbon dioxide emissions from humans.

The Production Gap Report – created with the purpose of tracking discrepancies between governments planned fossil fuel production and global production that should align with Paris Agreement [5].

FuelCell – A company that looks to develop hydrogen fuel cells for achieving low to zero carbon power providing a sustainable fuel source.

Mmol/g – millimole per gram