

Carbon Capture Technologies: Innovations, Challenges, and Environmental Implication

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Abstract

This review work provides a comprehensive overview of carbon capture and storage (CCS) technologies, their status, and future directions. It examines various capture methods, including pre-combustion, post-combustion, oxy-fuel combustion, and direct air capture, as well as emerging and hybrid technologies such as metal-organic frameworks, ionic liquids, and microencapsulation. The study discusses the limits of current technologies and attempts to point out innovations needed to ameliorate these challenges. It also explores strategies for widespread adoption of CCS, emphasizing the role of government policy formulation, implementation and industry collaboration. The review concludes by identifying research and development priorities and recommending approaches to accelerate the deployment of CCS technologies in order to meet global climate mitigation targets.

Keywords: Carbon capture, storage, energy efficiency, combustion, global

INTRODUCTION

There is an increase in global energy demand due to increase in population and emerging technologies, allowing the devastating impacts of global warming on distinct scenarios where nations and people work together to meet the Paris agreement goal of keeping the global temperature well below the 2.0 benchmark. Recently, the global energy use has risen in an exponential manner within the range of 8,588.9 Mt in 1995 to 13,147.3 Mt in 2015 [1]. Carbon capture and storage is a technology that is designed to capture carbon dioxide emissions as a result of burning fossil fuel from industrial processes, power plants, cement factories and refineries and sending them into geological formations or utilizing them in other processes thereby preventing them from being released into the atmosphere. The carbon capture and storage process typically has three stages, CO₂ capture, transportation and storage. The CO₂ storage can be in either depleted oil and gas reservoirs, saline aquifers or deep geological formations.

The relevance of carbon capture and storage in mitigating climate change cannot be over-emphasized, especially in the context of addressing the threat of climate change. The combustion of fossil fuel gives rise to greenhouse gases; and among the list of greenhouse gases, CO₂ is primarily the source of global warming and climate disruption. Carbon capture and storage provides a viable road map to significantly cut CO₂ emission from major sources such as power generating plants and industrial activities by capturing and storing or utilizing it before it is released into the atmosphere. The carbon capture and storage technology also helps in allowing the continued use of fossil fuels as major energy source while transitioning to low carbon energy systems [2]. Achieving the Paris agreement

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goal of keeping the world average surface temperature to well below 2°C entails large reduction in greenhouse gas emissions. Large percentage of the emissions come from hard-to-abate sectors namely cement, iron and steel industries. The large percentage of the CO₂ in the atmosphere contributes in depleting the ozone layer thereby resulting in global warming. To drastically reduce this emission, carbon capture and storage technology is employed [3]. According to the report prepared by United Nations Environment Program on emission gap in 2019, total greenhouse gas emission in 2018 was estimated to be 55.3 Gt CO₂; of which, 37.5 Gt CO₂ is attributed to fossil fuel CO₂ emission from energy generation and industrial activities. This rise in fossil fuel emission was as a result of increase in energy demand. One of the routes used in mitigating this anthropogenic emission is carbon capture and sequester technologies otherwise termed negative emission technology. Some of these technologies include but not limited to bioenergy carbon capture and storage, biochar, direct air carbon capture and storage, afforestation and reforestation, ocean fertilization, and ocean alkalinity enhancement [4]. The world is transitioning from high to low carbon economy. The motivation for this transition is the increase in the global average temperature which is associated with anthropogenic CO₂ emission from fossil fuel and industrial activities. In the last 12 decades, global CO₂ emission from fossil fuel and cement plant has multiplied 18-times from 2 in 1900 to 36 Gt-pa in 2020. The world temperature has increased by 1°C during this period. A lot of scientists believed that the increase in temperature is the cause of global warming. To this effect, there is an urgent need for countries to cut their carbon emission in order to reverse the trend of the global temperature increase. Carbon capture and storage can play a significant role in mitigating this emission [5]. Carbon capture and storage technology stands as one of the key tools in global attempt to fight climate change, giving a pathway in mitigating CO₂ emission originating from power generation and industrial processes. This innovative technology involves capturing CO₂ from gas-fired and coal-fired power plants, or industrial processes, thereby securing and injecting them into geological formations thereby preventing their release in to the atmosphere [6].

TYPES OF CARBON CAPTURE TECHNOLOGIES

Pre-combustion Capture

This is usually incorporated in coal fired thermal power plant, and the process involves gasifying the coal to produce a synthetic gas consisting of carbon monoxide (CO) and hydrogen. The carbon monoxide is made to react with water (in a water-gas shift reaction) to produce carbon dioxide and hydrogen. The CO₂ is then captured and the hydrogen is sent to gas power plant as fuel to generate electricity [7]. One of the most viable frequently reported pre-combustion CO₂ capture is the physical solvent absorption capture. In this method, there is no chemical reaction, so the driving force for the CO₂ absorption is the solubility of CO₂ in solvent which decreases with temperature and increases with pressure in line with Henry's law. The generation of physical solvent is through some combination of (a) temperature increase, (b) pressure reduction and/or (c) sweep gas. The captured CO₂ is released to the atmosphere unless there is CO₂ compression and storage facility, such as the Great Plains Synfuels plant in North Dakota which captures the CO₂ and H₂S using Rectisol solvent where it is compressed and transported to sour soil field in Canada [8]. For the integrated coal gasification, combined cycle pre-combustion power plant consists of several units. The gasifier operates at a temperature between the range of 1200–1482°C at a pressure of 41 bars and is used to react with coal with limited water and oxygen to produce syngas and small amounts of unwanted gases. The next phase involves cooling the syngas mixture and recycling the unreacted carbon back to the gasifier so that the overall efficiency of the process is improved to capture higher amount of carbon dioxide, two water-gas shifts are employed rather than one. With the second one operating at a lower temperature. The water gas shift reaction is initiated which helps in improving the amount of CO₂ and H₂ at the same time lowering CO and H₂O.

Before the water gas shift reactor, the unwanted gases can be classified as untreated syngas and proceeds through numerous gas treatment steps. The substance is separated by Sulphur processor since it is a highly desired component in several industries. The treated syngas if desired can be fed into a gas processor to ensure that the syngas mixture is free of any unwanted components. Lastly, CO₂ is captured and compressed, with the likelihood of using it to enhance oil recovery or to sequester it in geological

formations [9]. Another work by Zhou *et al.* stated that in an integrated gasification combine gas cycle power plant, a feedstock such as coal is partially oxidized at elevated temperature and pressure to produce synthesis gas, otherwise syngas, which mainly constitutes of CO₂, CO and H₂ [10]. The CO is further converted into CO₂ through water gas shift reaction. The generated CO₂ can then be captured and separated before the H₂ rich fuel is combusted to generate thermal energy. The shifted syngas is rich in CO₂ and at an elevated pressure, which provides for an easy removal. The process of capture is highly efficient but is generally more expensive than post combustion capture. In most pre-combustion carbon capture, the process needs relatively high temperature for the re-generation of solvent, this can lead to substantial reduction in the solvent. This problem can be overcome using ionic liquids, a new type of solvent that is receiving extensive studies as a substitute for carbon capture due to their high CO₂ solution capacity, high chemical and thermal stability and negligible volatility.

Post-combustion Capture

The post combustion carbon capture technique can capture CO₂ and other gases from burning fossil fuel based on physical/chemical adsorption/absorption mechanisms. Based on the principals involved in the capture process, it can be categorized as adsorption, absorption, membrane separation and chemical reactions. Post-combustion capture technique by adsorption can further be classified into pressure swing, temperature and vacuum swing.

Temperature Swing Adsorption

The temperature swing adsorption is related to adsorbing volatile organic component from the air. In TSA, adsorption and desorption cyclically occur by adapting the operating temperature. This adsorption method involves numerous connected vessels with fixed, moving or fluidized beds [11]. Adsorption mostly occurs at lower temperature where desorption requires heating of the adsorbent bed and therefore a cyclic mode of adsorption and desorption is applied. The CO₂ adsorption is favored at lower temperature range of 40–60°C while desorption is favored at high temperature range of 140–160°C. The implication here is that the adsorption columns are sequentially operated at 60°C to efficiently capture the CO₂ and heated mostly by hot air or steam at 140°C to release CO₂ and finally to 160°C to remove impurities if present. A massive air flow rate is required in regenerating the bed but dilution with the CO₂ stream is possible due to the poor heat capacity of air, and this problem can be avoided when steam is used for the regeneration or totally avoided when the desorbing bed is heated electrically [12, 13].

Pressure Swing Adsorption

The pressure swing adsorption is a gas separation technology that employs a solid adsorbent material to selectively adsorb a target gas component from a gas mixture. The adsorption process occurs at high pressure while the desorption process occurs at low pressure to regenerate the adsorbent. The steps involved in the separation are pressurization, adsorption, a depressurization and then desorption. In pressure swing adsorption, CO₂ is adsorbed onto the surface of a solid sorbent at elevated pressure and is released at a lower pressure. The principle of operation depends on molecular characteristics and affinity of N₂ and CO₂ for the solid sorbents. CO₂ is selectively adsorbed by the adsorbent bed at elevated pressure while ignoring N₂ due to affinity. When the bed is super saturated with CO₂, regeneration can be achieved at low pressure thereby releasing the adsorbed CO₂. The procedure is repeated for the next cycle. The combination of temperature swing adsorption and pressure swing adsorption can achieve 99% CO₂ purity and 90% CO₂ recovery [12]. Another work reported by Lin *et al.* summarized the pressure swing adsorption into four stages [14]. In the first stage, the adsorption stage, the bed is exposed to 10 bar pressure for 40 s and is fed with combination of 38% methane and 62% CO₂. The CO₂ having greater polarity, its adsorption will be more than methane in this stage. In the next stage, the pressure drops to atmospheric for 20 s and the adsorbed CO₂ is removed from the adsorbent.

Vacuum Swing Adsorption

This process has been used industrially for CO₂ separation for decades and has the advantage of using the adsorbent for an extended period of time, simplicity and low energy consumption. The adsorption

is done under atmospheric pressure and desorption under vacuum. The high efficiency desorption under vacuum enables the use of a single adsorption/desorption vessel in which high efficiency separation and yield are obtained. In a vacuum swing adsorption activated with carbon adsorbent, a 17% flue gas concentration can be concentrated to 99% with a recovery of 68% [15]. Both PSA and VSA depend on the variation of the pressure in regenerating the sorbent. Specifically, in PSA, CO₂ is captured at elevated pressure whereas it is desorbed and the spent sorbent is regenerated lowering the pressure to atmospheric. Even though this technique finds application in the industrial sector, it has a drawback of emitting flue gas at atmospheric pressure with a relatively low CO₂ concentration (<20% vol). Therefore, large volume of gases would be compressed, which obviously destroys the economics of the process. Another setback is that the sorbent selectivity for CO₂ reduces with increase in pressure, thus making it difficult to achieve high purity gas in the desorption gas [16].

Electric Swing Adsorption

The first application of electric swing adsorption came into play in 1997 based on activated carbon adsorption of volatile organic compound from the air. The adsorbent is heated through Joule effect by supplying low voltage electric current thereby regenerating them, hence reducing energy cost for the capture without needing to heat the adsorption units and its accessories. The advantage of this capture method over the temperature and pressure swing adsorption is that it requires less heating, fast heating rate, better adsorption kinetics and dynamics as well as independent control of gas and heat flow rates. The potential suitable candidate, semi-conductive activated carbon fiber materials, have a high specific surface area, high adsorption capacity, and high resistance to water vapor [12].

Post-combustion carbon capture based on adsorption is the most advanced technology due to its proven capability in treating large volumes of gas and its simplicity in retrofitting to existing facilities. However, the application of this method commercially has limitations mainly due to high cost of capital and substantial energy demand for the regeneration of the adsorbent. The energy penalty for this approach takes up 80% of the operational cost as amines regeneration is carried out at elevated temperature 120–150°C to compensate for the poor CO₂ desorption kinetics. Since amine solutions are 70–80% water, maintaining such a high regeneration temperature implies heating and boiling the water which result into energy waste. This energy waste can be minimized when the amine regeneration can occur at a temperature below 100°C. Several studies have shown that introducing a solid acid catalyst can improve the desorption of CO₂ at lower temperature, for instance, 85–100°C resulting into the reduction of heat duty requirement for the regeneration of the amine [17].

Adsorption CO₂ capture is method of separating CO₂ concentrations from gas mixtures such as flue gas or air. This approach employs the application of solid adsorbents which has high affinity for CO₂ capture, as the gas molecules are brought in contact with the adsorbent, the CO₂ molecules become attracted to it thereby separating it from the remaining gases. Some of the widely used adsorbents include activated carbon, zeolites and metal organic framework. At the saturation level of the adsorption process, the adsorbent material can be regenerated by applying pressure or heat or the combination of both. Adsorption based carbon capture is the most efficient because of its low energy demand [18].

Chemical adsorption of CO₂ from mixture of gases with the use of aqueous amine sorbents is reported to be the most mature and effective technology for carbon dioxide capture, but its industrial application is limited due high cost of energy for sorbents regeneration. Non-aqueous sorbents have been found to be better candidates to the conventional amines especially when combined with a catalyst, the study showed decrease in energy cost for the sorbents regeneration [19].

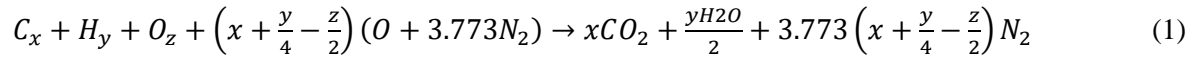
Oxy-fuel Combustion

It has been established by many researchers that oxy-fuel combustion is one of the effective ways of CO₂ capture from gas mixtures. The foundation for oxy-fuel carbon capture relies on using pure oxygen as against air which contains nitrogen as the intake charge to react with fuel for combustion. This will

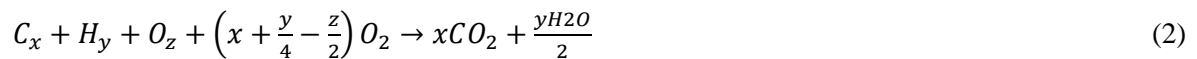
result in the exhaust emissions as being only carbon dioxide and water vapor, while the harmful emissions related to nitrogen elements, such as NO_x are largely reduced. The advantage of this process is that the CO₂ can almost be eliminated and separated from the exhaust which can be achieved through the condensation of the water vapor. As a result, almost pure CO₂ can be compressed and stored.

The main distinction between the oxy-fuel and the conventional combust is illustrated using the chemical reaction below:

For the conventional air combustion:



For the oxy-fuel combustion:



The primary difference between the two combustions is the reactants, where in Eq. (1), air which contains nitrogen is made to react with the fuel as against pure oxygen in Eq. (2) [20]. One good advantage of oxy-fuel capture process is that the combustion products consists mainly of CO₂, H₂O and SO₂. Separation of the H₂O is by condensation. SO₂ is easily eliminated via electrostatic precipitation and desulphurization. This purification will result in pure CO₂ stream for compression, storage, transport and utilization [21]. Different carbon capture methods are shown in Figure 1(a)–(c).

Direct Air Capture

According to the International Energy Agency (IEA) 2020, direct air capture is removing 1000s of tones of CO₂ per annum. The definition of DAC is so broad that there are numerous promising and developing capture methods. The two, which have advanced in development are the solid sorbent and the liquid solvent DAC. Cryogenic direct air capture takes advantage of the sublimation point of CO₂ to generate solid CO₂ from the air which can either be stored as solid or be re-sublimated to produce gaseous CO₂ of high purity. Moisture or humidity swing adsorption employs anionic exchange resins to capture and give off CO₂. Carbon dioxide is an acid gas, by implication, the sorbent (solid or liquid) that will be used to capture the CO₂ from gas streams are usually conditioned to be basic in nature for the sorption to take place. The next stage is to release the captured CO₂ (desorb) from the sorbent (regeneration) which returns the sorbent to its pre-sorption state for the next round of the capture. The most

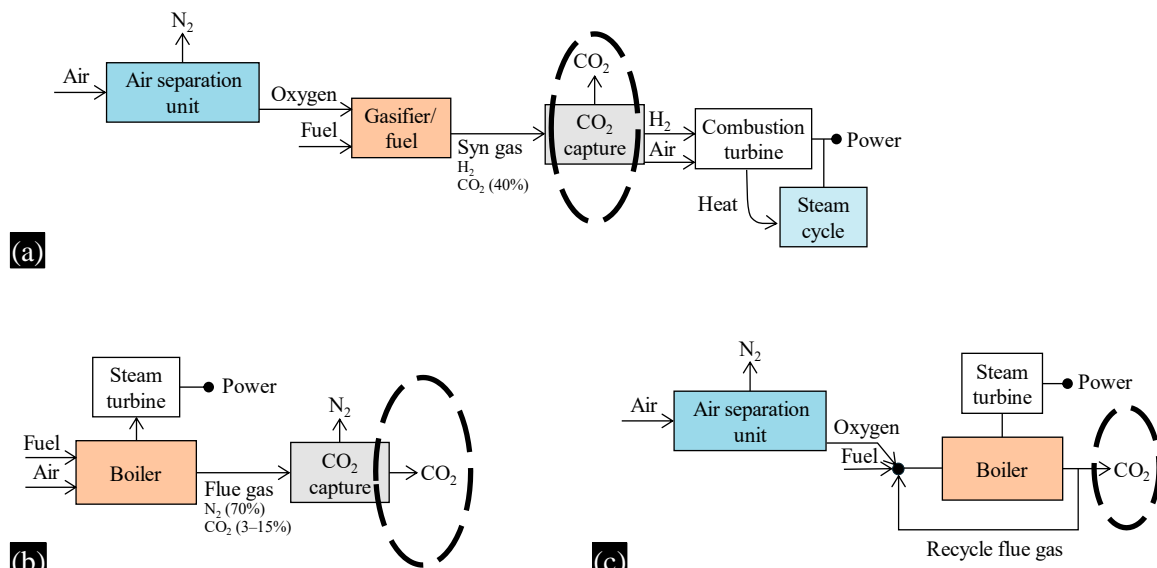


Figure 1. (a)–(c) Different carbon capture methods.

important part of DAC is the sorbent and it must therefore fulfill certain set of conditions. The first condition to be satisfied is that the capture must be carried out at ambient condition of the air because for instance, it will not be economical to pressurize, cool or heat the air with the exception of cryogenic and membrane based technologies before the CO₂ is being captured, and the energy to be used for the capture must not come from carbon-based sources such that more CO₂ is not released during the capture. The energy must come from renewables such as solar, wind, hydro or nuclear. After meeting the first condition, the following sorbent properties must be satisfied depending on the application: high selectivity, high capacity, fast transport and kinetic properties, high thermal and chemical stability, good mechanical properties in case of solid sorbent, ease of loading, resistance to fouling, ease of regeneration, and low cost [22].

These sorbents will stick to CO₂ in arid conditions and give off CO₂ when it is brought in contact with water, which has the potential to reduce energy requirement at the expense of increasing water consumption. Another work by Voskian and Hatton proposed an electro swing process where CO₂ sticks to polyanthraquinone-carbon nanotube composite upon charging and is evolved upon discharge, having the advantage of eliminating thermal energy requirement and producing high purity CO₂ stream [23]. Other method includes the use of intentionally manufactured alkaline feedstocks, e.g. caustic calcined magnesia (MgO), to capture CO₂ from the air, or the use of aqueous amino acid solution to absorb CO₂, regenerated by crystallization of an insoluble carbonate salt with a guanidine compound.

The two most advanced DAC methods are the liquid solvent and the solid sorbent. In the solid sorbent approach, CO₂ gas molecules hierarchically interact with porous materials that can capture CO₂ from incoming gas mixture through adsorption. Solid sorbent can remove CO₂ from gas mixtures through weak intramolecular forces called physio-sorption or strong covalent bonding referred to as chemisorption. The strength of the bond between a CO₂ molecule and the sorbent surface may be characterized as the heat of adsorption. In clear terms, physio-sorption occurs when the heat of adsorption is less than approximately 15 kcal/mol. Solid sorbent can be enhanced with amine surface functionalization that improves their interactions with CO₂ molecules thus making them more selective toward CO₂. Currently, research methods are exploring countless support structures to be used as solid sorbent for DAC: zeolites, metalorganic frameworks, activated carbon, silica materials, carbon nanotubes, porous organic polymers, and carbon molecular sieves [24].

In the liquid solvent-based approach, CO₂ gas is absorbed into a liquid solvent, resulting in a CO₂ gaseous exiting stream and a CO₂ rich liquid exiting stream. These types of approaches usually use structured packing to improve the contact surface area between the liquid and the gas phases. The solvent based approach requires a strong basic hydroxide solution to absorb CO₂. This is followed by an anionic exchange that results in precipitated calcium carbonate. However, the extreme dilution of CO₂ in air requires a strong base which is used for adequate separation, which further drives the high energy requirement for this method [24].

The conventional process used in direct air capture are based on sorption technologies. Despite proven effectiveness of this process, it requires huge amount of energy for the regeneration of the sorbents. Membrane technology is one of the leading approaches in capturing CO₂, mainly because of its lower cost, straight forwardness in setup and operation, and a smaller footprint. The most important property in membrane separation is its permeance, hence the selective membrane thickness should be reduced to nanometers in order to increase this property [25].

Emerging and Hybrid Technologies

Emerging technologies entails advanced materials and processes for carbon dioxide capture having advantageous effect on energy penalty, adsorption capacity, stability, cost and climate. Some of which are discussed below.

Metal-organic Frameworks (MOFs)

These are solids that are crystalline and porous in nature, that are having open structures with large dimensions for gases with fine dispersal properties which have over the recent decades attracted significant attention. MOFs consists of three-dimensional coordination polymer networks, fabricated by the combination of metal ions/clusters with organic linkers/ligands. A limitless number of MOFs have been realized by altering the composition of linkers in the organic phase or the metal ions. Due to their unique structural properties such as high specific surface area, active metal sites, and tunable pore structures, MOFs have high BET surface area and high pore volume along with easier manipulation of the pore structure and surface functionalization, which are the other interesting features of MOFs, which present a strong case for their application in the field of CO₂ capture [26]. Another work reported by Singh *et al.* has shown that MOFs are highly attracted to capture CO₂ due to increased facet area and pores volume [26]. The adsorption of metallic-organic frameworks decreases with increasing temperature and increases with increase in pressure. The adsorption capacity of MOF-74 has been reported as 5.5 mmol CO₂/gMOF at 40°C and 0.15 bar which increases to 8.0 mmol/gMOF at 1 bar and 15°C [27]. It has been recently presented and concluded via a review that MOFs are promising candidate for adsorption capture for the next generation technology [28]. Adsorbents such as MOFs, zeolite and activated carbon are reported to be unsuitable at elevated temperature due to decrease in their adsorption capacity. MOFs have low adsorption capacity at low CO₂ partial pressure in comparison to zeolite and activated carbon. The adsorption capacity of MOF-177 at 35 bar and at ambient temperature has been reported to be 1.47 g CO₂/gMOF [28].

Ionic Liquids (ILs)

The synthetization of ionic liquids using organic cations and organic/inorganic anions is done with varying compositions with the aim of increasing the solubility of CO₂ substantially. The ionic liquids adsorb CO₂ at room temperature in the presence of philic groups and are called task-specific ionic liquids (TSILs), having a melting point below 100°C. The solubility in ionic liquids enhances with increase in pressure and decreases with temperature. Some of the favorable properties of ionic liquids that make them suitable and attractive are low volatility and boiling point (<100°C) and are considered novel solvents due to their advantages (that is, high CO₂ selectivity and solubility, low regenerative heat, thermal stability and minor/negative vapor pressure). However, they have low adsorption capacity than amines, high viscosity as well as cost [29].

Hybrid Membrane

High energy for regeneration and high cost are the two major problems associated with using a single technique for capture of CO₂. The hybrid technology combines various techniques to compensate for the individual limitations. The hybrid hollow fiber membrane-MEA technique was used by Scholes *et al.* during a post-combustion capture and was found to be advantageous in terms of low energy consumption and cost [30]. An improvement in the CO₂ separation and capture performance has been reported when ionic liquids were combined with membrane as a result of the formation of carbonate and bicarbonate, which can be regenerated easily. An increase in CO₂ separation efficiency using the membrane-assisted gas absorption process was reported by Atlaskin *et al.* [31]. Although ionic liquids are largely superior to traditional amine solutions in terms of CO₂ solubility, they have the disadvantage of high viscosity and slow mass transfer. It is evident that ionic liquid can selectively absorb CO₂ molecules due to its affinity. The hybridization of membrane with ionic liquids has the following advantages: (1) the selectivity of membrane material will be significantly improved due to the selective absorption of CO₂ by ionic liquids; (2) the function of the ILs is no longer to store CO₂ after capture but to diffuse it to the other side thereby resulting in reduction in the amount of ILs used which consequently reduces the cost of preparation of ILs; and (3) the membrane material is generally thin, and the difference in concentration of the solute serves as a driving force for transfer of CO₂, so the disadvantage of slow diffusion of CO₂ in ILs is concealed [32].

Molecular Sieves

These are extremely permeable materials suited for hole sizes of gas molecules to separate a particular gas easily. The hybridization of ionic liquids with a sieve enhances the separation and capture of CO₂. The size-sieving ability of membranes can be improved using porous particles and ionic liquids to promote the selectivity of gas. The molecular sieve carbons have an additional advantage of the ability to both adsorb and desorb the molecules in cycles with less energy consumption. However, the complexity in the design of molecular sieve is a barrier in their applications [29]. Another work reported by Cao *et al.* on the combination of membrane and adsorptive reactors for CO₂ separation highlighted that the hybridization of the two techniques helps in improving process efficiency, reducing energy consumption as well as minimizing the formation of by-products [33].

Cryogenic Separation

This is a physical separation process that is based on differences between the boiling points and the de-sublimation properties of the components in the gas mixture. This method is valid to capture CO₂ from flue gases mixture containing more than 50% carbon and is suitable for pre-combustion and oxy-fuel combustion capture. This method has less sensitivity to impurities and required great amount of energy for the CO₂ separation during refrigeration cycle [29]. Cryogenic carbon capture technology, often called low temperature CO₂ capture depends on phase change, thus capturing the CO₂ from the flue gas in the form of solid or liquid. This technology can capture CO₂ at atmospheric pressure with high rate of purity. Some of its shortcomings are high energy requirement due to cooling, feed composition must be stripped of water so as to prevent ice plugging, and also it is not economical for dilute CO₂ feed streams [34].

Nanofluid

Significant improvement in CO₂ absorption, stability, and energy efficiency is reported by the addition of nanoparticles to a solvent depending on the nanofluid, particle size, CO₂ concentration, pressure and temperature. A 32% CO₂ absorption rate using carbon nanotubes was reported. However, the CO₂ absorption efficiency using nanofluid is lower than Nany mixtures and this needs to be investigated considering the regeneration of solvent, energy penalty and economic viability. The use of 0.05 wt% of nanofluid reported an increase in CO₂ absorption of 32% using CNT nanoparticles, while 16% enhancement using SiO₂ nanoparticles under specific conditions [29]. Reports by Karamian *et al.* pointed out the effects of Al₂O₃, Fe₂O₃, and SiO₂ nanofluids on CO₂ absorption and discovered respective mass transfer coefficients as 117, 103 and 88% higher than the solvent without nanofluids [35].

Microencapsulation

Microencapsulated carbon sorbents are identified as one of the promising materials for enhanced CO₂ capture due to their drastically increased gas-liquid contacting area. In this concept of microencapsulation of carbon sorbents, the CO₂ sorbents are encased in a polymer material that is permeable through microfluidic methods to generate microcapsules having outer diameters ranging from 100–600 μm and shell thickness of 10–50 μm. By virtue of their increased surface area, MECS are endowed with significant enhancement in CO₂ capture kinetics when compared with CO₂ chemisorption systems. Furthermore, MECS transform the liquid solvents physically to solid sorbents combining the advantage of liquid solvents in reaction kinetics and solid sorbents in flowing patterns. Therefore, MECS are especially good for handling solvents with easy precipitation (e.g., carbonate) or with high viscosity (e.g., ionic liquid). They essentially have greater advantage of having low energy penalty, or low corrosion [36].

The surface area of the core absorbents increases with microencapsulation by housing the absorbents in semi-permeable microcapsules, which makes CO₂ and water to flow thereby achieving the advantages of liquid solvents and solid sorbents, with CO₂ absorption of 100 times faster than the use of standalone solvents/sorbents. An energy decrease of about 11.8% has been reported of using microencapsulation than the amine [29].

Phenoxide Salt

In 2019, Wheatly *et al.* reported the first exploration of phenoxide salt (KOPh) for capturing CO₂ in order to replace amine solvents. A poor performance was observed but performance was enhanced when it was made to combine with mono-ethylamine (MEA) [37]. With the addition of KOPh in MEA, the CO₂ absorption is enhanced without decrease in the rate of absorption. The presence of phenoxide in excess results in producing a large quantity of bicarbonate. During the post combustion technique, less energy is required because of the low stability of bicarbonate when compared to carbonate. It has been reported that MEA (1 mol/l) with KOPh (3 mol/l) adsorbs 88% of CO₂ with an absorption capacity of 3.5 mol/l, which is higher than the mixture consisting of MEA and AMP in the molar ratio, and absorbs 70% from the similar absorption capacity (3.51 mol/l) [29].

FUTURE DIRECTIONS AND RECOMMENDATION

Research and Development Priorities

In the last two decades, there was dramatic growth in research and application of CO₂ capture methods and subsequent chemical, biological and geological sequestrations. The use of amines as absorption method is the most mature technology in CO₂ capture and it is the only one in large scale applications, while persistent research interest in absorption and filtration membrane is evident despite challenges in industrial applications. The most research capture method is post combustion due to its lower cost and relative ease of retrofit into existing plant [38]. Bioenergy carbon capture and storage technology is considered as one of the most promising negative emissions technologies, having many modelling scenarios in place showing its potential. However, commercialization of this technology is yet to be achieved and over reliance on this technology has created uneasiness among experts and policy makers in the field, highlighting sustainability as the major concern [39].

Innovations Needed to Overcome Current Limitations

The advance capture technologies have the ability and are found promising to lessen CO₂ emissions, even though they all have their limitations. Some of these limitations are: presence of impurities, low partial pressure of CO₂, absorption capacity, high regeneration energy, high cost, and ability to be retrofitted into the existing plants. Some of these challenges can be overcome by the new generation technologies such as amine blends, MOFs, membrane, cryogenic or the early stage technologies such as ionic liquids, oxy-fuel combustion, chemical looping or the combination of these technologies in a hybrid manner.

The physical solubility of the CO₂ can be enhanced by the addition of organic co-solvents with water-lean/non-aqueous amines which will result in increasing the regenerative energy thereby decreasing the regeneration cost. Blending multiple amines may be promising as they may complement one another. The addition of piperazine for instance improves the performance with a 22% decrease in energy consumption. The CO₂ capturing ability and removal efficiency is enhanced by increasing amine's flow rate. The CO₂ can be absorbed at low temperature (0–20°C) and desorbed at (100–200°C) with chilled ammonia processes with a tremendous decrease in energy consumption but associated with high loss of ammonia. The high energy demand and cost can be reduced by using carbonate solutions over amines but with a disadvantage of slower absorption kinetics [29].

Strategies for Widespread Adoption of Carbon Capture Technologies

The acceptance of innovative low carbon technology by the public is very crucial for the successful rollout of the production infrastructure and the market adoption of CCUS products by consumers. We refer to the definition of acceptance as active or passive approval of the development, implementation and the use of technologies. The rolling out of large scale technologies affects the public at various levels: not only the general idea of the specific technology and its derived products have to be adopted, but the public must also support or at least tolerate the required technical infrastructure and its consequences in terms of land use, and visibility [40]. With capital cost at the forefront of carbon capture and storage technologies adoption, the developing countries can receive financial aids from international

programs such as Nationally Appropriate Mitigation Action (NAMA) if they subsume the policy in their submitted Intended Nationally Determined Contribution (INDC). The financial intervention of the private sector is of great importance for financing and deployment of CCS and R&D projects. The leading requirement for CCS deployment are the national and international initiatives, yet it will not enhance market diffusion explicitly. Some market-based instruments which include subsidies, carbon taxes and emission trading systems, supplying the required economic incentives, act as an incentive for CCS development and adoption. Strategies in ensuring the deployment of the CCS technology can be through funding in research and development activities, providing indirect incentives in private sector for R&D activities, supporting opportunities by transferring knowledge [41].

Role of Policy and Industry Collaboration

The slow deployment of CCS technology is as a result of the non-technical barrier. Outside of northern Europe and the USA, majority countries have no carbon tax or credit, and as a result, there is little or no incentives for companies to sequester CO₂ in geological formations. A good enough carbon pricing incentive will motivate industries to capture and store CO₂. In the USA for instance, 45Q carbon tax credit of \$ 35/t of CO₂ sequestered in EOR projects and \$ 60/t of CO₂ sequestered in geological formations. However, the value for carbon price is dependent on energy cost and varies from country to country. In addition to carbon pricing, a consistent, sustainable and predictable energy policy will go a long way in encouraging industries to heavily invest in carbon capture technology. Policies such as setting target for renewables in various energy consumption sectors and subsidy for low carbon technologies such as electric or hydrogen fuel vehicles are needed to encourage heavy investments in these technologies. Regulations should be put in place as to transportation of CO₂ between countries and its disposal and monitoring in subsurface reservoirs. There is also need for sponsored campaign in the importance of public acceptance so as to enable government promulgate policies that favor CCS. People who believe in human-induced climate change are very unlikely to believe or accepts these policies. This perception can however be changed by engaging trustworthy stake-holders such as teachers, government scientist and academics [5].

CONCLUSION

Carbon capture and storage (CCS) technologies are a critical pathway for mitigating climate change and reducing CO₂ emissions from major industrial sources. This review has highlighted various capture methods, including pre-combustion, post-combustion, oxy-fuel combustion, and direct air capture, as well as emerging and hybrid technologies. While significant progress has been made, and various improvements being researched, challenges remain in terms of energy efficiency, cost-effectiveness, and scalability. To accelerate the widespread adoption of CCS, continued research and development, innovative policy frameworks, and strong industry collaboration are essential. Addressing these challenges will be of paramount importance in realizing the full potential of CCS technologies and their contribution to global climate goals.

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