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A Comparative Review of Post-Combustion Capture and Direct Air Capture of CO_2

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Abstract

Original Research Article

Mitigating anthropogenic CO_2 emissions has been a subject of incredible urgency in recent years. Carbon capture and storage (CCS) has emerged as a promising means of cutting emissions, with post-combustion capture and direct air capture (DAC) both gaining traction as methods of offsetting emissions from point sources and the ambient atmosphere. Each of these carbon capture methods rely on absorbent or adsorbent materials to function, whose properties can vastly impact capture performance. In this work, 14 materials are analyzed, with qualitative descriptions and performance data of each material based on existing review papers and representative case studies being presented. The review highlights limitations in the field in standardizing the reporting of experimental data, complicating the direct comparison of different materials' efficacies. While no single CCS technology is found to be unequivocally superior, the promising performances of certain materials in earlier stages of development emphasize the importance of investing further in emerging post-combustion capture materials. This study concludes that CCS technologies are a necessary tool in ultimately reaching net zero emissions due to their role in neutralizing sectors resistant to decarbonization, but they should not be relied upon to substitute the transition to renewable energy, as the prevention of emissions should take priority over the abatement of emissions.

Keywords: Carbon capture, direct air capture, post-combustion capture, climate change, CO2 emissions, absorption, adsorption.

1. INTRODUCTION

The urgency of reducing global warming has never been more evident. The summer of 2023 was reported to be the single hottest summer on record [1]. Curbing anthropogenic carbon dioxide (CO_2) emissions and atmospheric CO_2 accumulation is crucial to counteracting global climate change. In the timeframe between 1980 and 2021 alone, global atmospheric CO_2 concentrations rose more than 20%, from 339 ppm to 415 ppm [2]. In response, the Paris Climate Agreement was adopted at COP21 in 2015, emphasizing the need to cut down on CO_2 emissions. This agreement aimed to restrict the global average temperature to 1.5°C above pre-industrial levels by 2100 [3]. In recent decades, carbon capture and storage (CCS) technologies have gained traction as a potentially crucial means of limiting the amount of CO_2 emitted into the atmosphere, especially in sectors that are notoriously difficult to decarbonize, such as the steel and cement industries [4]. The International Energy Agency lists CCS as a necessary supplemental innovation in order to achieve net zero emissions by 2050, with a failure to implement CCS projected to increase the renewable energy demand significantly [5].

Currently, post-combustion capture and direct air capture are two of the most promising approaches. Post-combustion capture involves the use of absorbent or adsorbent materials to selectively capture CO_2 from industrial flue streams after sulfur oxides and nitrogen oxides (SO_x and NO_x) and particulate matter have been removed by scrubbers and electrostatic precipitators, respectively. Post-combustion systems can typically be retrofitted onto existing power plants or integrated into the construction of new plants. They show promise with potential to bring a given power plant's greenhouse gas emissions to near zero [6]. Conversely, direct air capture (DAC) requires the construction of new dedicated DAC plants and aims to capture CO_2 from the ambient surrounding air, having negative emissions potential [7].

In this paper, the Department of Energy's Carbon Dioxide Capture Handbook's classifications of post-combustion capture were analyzed in comparison with direct air capture case studies [8]. Among these various technologies, their stages of development range from laboratory-scale research to being used in industrial settings. This paper first aims to assemble and discuss the function of common CCS technologies to understand what is currently available for addressing CO_2 capture. Next, the viabilities of these CCS technologies are presented in a table of qualitative "advantages" and "disadvantages," as well as a table quantitatively comparing their CO_2 capture capacity and technology readiness level (TRL). Finally, these results are discussed in the context of their ability to meet current global carbon capture needs.

2. DATA COLLECTION

This section outlines the methodology used to synthesize findings from existing studies regarding the CCS technologies selected for this paper. Qualitative descriptions of each technology were determined by analyzing information from the Carbon Dioxide Capture Handbook, other comparative review papers, and a representative experimental case study for each technology. The characteristics examined included the materials' stability under capture and regeneration, scalability, longevity, cost, conditions that inhibit performance, and other notable factors specific to each material. Quantitative data was collected from each technology's representative case study, and the parameters of carbon capture efficiency and operable temperature were recorded. Carbon capture efficiency was recorded in the unit of mmol CO_2 captured per gram of capture material, and the necessary unit conversions were performed to standardize every material's carbon capture efficiency to this unit. The CO_2 concentration of the flue stream used in each case study was also recorded alongside the capture efficiency to more holistically gauge the functionality of each CCS material. This is because the CO_2 concentration of the flue stream when testing a respective material directly correlates to its experimental CO_2 capture performance [9]. Operable temperature was recorded in the unit of degrees Celsius, and the necessary unit conversions were also performed to standardize the temperature data. The TRL of each material was also determined by analyzing the description of each technology's maturity based on its representative case study, and assigning it a TRL score from 1 to 9 based on the TRL scale [10]. Table 2 provides a synthesis of these quantitative parameters.

Factors such as operational cost, CO_2 equivalence, and life cycle analysis were also initially considered in order to gauge each technology's long-term performance, but there wasn't sufficient information available on these parameters for most of the technologies being analyzed due to the novelty of many of these CCS approaches. Post-combustion capture materials were further categorized into the classifications of solvent-based capture, sorbent-based capture (further split into physisorption and chemisorption), and membrane-based capture. The scope of our methodology was limited to one DAC case study because the majority of DAC approaches quantified capture success through units that aren't comparable to the units used for the other materials discussed in this paper. For example, carbon capture capacity was measured in mmol CO_2/g material for all post-combustion capture materials, but many DAC systems quantify capture capacity in terms of energy expenditure, using units such as kJ/mol CO_2. However, the written portion of the results section also discusses DAC in its larger context to account for this.

3. RESULTS

In this paper, post-combustion capture materials are classified as solvent-based, sorbent-based, and membrane-based, and the method of direct air capture is also analyzed. For each CO_2 capture method, a synopsis is provided outlining the method's respective utility in a broader sense. For a comparison of the methods based on the representative case studies selected for each method, Table 1 provides brief qualitative descriptions of each method while Table 2 lists the quantitative data associated with each method.

3.1. Solvent-Based Capture

Solvent-based carbon capture involves the reactive absorption of CO_2 at the gas-liquid interface. This is where CO_2 diffuses from the gas phase to the interface, reacts with the solvent, and then diffuses from the interface into the bulk liquid. The solvents used for carbon capture generally face a viscosity tradeoff. Specifically, solvents with low viscosity, characteristic of aqueous solvents, demonstrate a high rate of CO_2 mass transfer from the gas to liquid bulk at the cost of higher heat requirements during regeneration to allow for moisture evaporation. Conversely, more viscous solvents have slower rates of mass transfer but lower thermal regeneration requirements [8].

3.1.1. Aqueous Amines

Amine absorption and stripping involves the chemical absorption of CO_2 via aqueous amines, followed by a stripping process that releases the absorbed CO_2 for storage and regenerates the amine solution to be recycled. The requisite technology is well-established and has been commercialized for decades, albeit not necessarily for CCS purposes. Example uses for amine scrubbing include natural gas purification, refinery gas processing, and chemical manufacturing [11]. The use of amines in aqueous solution is beneficial in that the solution's water content reduces its viscosity and corrosivity, but the high water content comes with the drawbacks of slowing solvent circulation rates and hindering working capacity as well as increasing the energy penalty during amine regeneration due to the thermal cost of evaporating water [8]. The process of amine regeneration via stripping is very expensive as a result, hindering the economic viability of amine-based capture despite its low cost when strictly capturing CO_2. Amine solutions are prone to amine degradation due to other gases and impurities in the flue stream, so the technique requires the desulfurization and denitrification of flue gas to work optimally. However, amine solutions also exhibit resistance to thermal and oxidation degradation, as well as low volatility [11]. Monoethanolamine is the standard for amine-based capture, commonly selected over secondary/tertiary amines with higher CO_2 carrying capacities due to its faster reaction kinetics and biodegradability [12].

3.1.2. Non-Aqueous Amines

Carbon capture with non-aqueous amines involves a similar amine-based absorption and stripping process, but uses either hydrophobic amines or organic liquid solvents instead of a water-based solution. In comparison to traditional aqueous amines, non-aqueous amine-based solvents similarly resist thermal degradation, but suffer from poor mass transfer of CO_2 from gas to liquid bulk (due to high viscosity) as well as the formation of unstable carbamates and protonated amines when reacting with CO_2. During solvent regeneration, non-aqueous amines have lower heat requirements but worse cyclic capacities than their aqueous counterparts, holding up worse after multiple regenerations [13]. Amine-organic solvent mixtures, which use organic liquid solvents instead of water, are being investigated due to requiring 30% lower solvent circulation than monoethanolamine and using flash vessels for regeneration over strippers, saving costs on pumping and regeneration respectively [8].

3.1.3. Phase Change Solvents and Ionic Liquids

Ionic liquids exhibit functional groups with high CO_2 affinity, allowing for selective binding to CO_2 in a flue gas stream. Ionic liquids remain in their liquid state for long periods of time. One reason for this is their low vapor pressure and thermal stability, which results in minimal solvent loss to evaporation. In addition, they are nontoxic, have high polarity, and exhibit versatility in both physical and chemical absorption [11]. These properties make ionic liquids an excellent candidate for developing phase change solvents, which involve the solvent undergoing a phase change into a CO_2-rich phase and a low-concentration lean phase. During absorption, CO_2 forms carbamates and is redirected into the rich phase while the equilibrium pressure in the lean phase stays low, maintaining a high concentration gradient within the system so that more total CO_2 is ultimately absorbed before the system reaches equilibrium [14]. Phase change solvents demonstrate high regeneration efficiency, as only the CO_2-rich phase has to undergo regeneration and the lean phase can be reused as is. However, the use of phase change solvents requires supplemental equipment to filter the remaining slurry post-absorption and maximize the surface area between solvent and CO_2 because traditional contactors don’t work for phase change solvents [8]. Ionic liquids also have the drawbacks of high synthesis costs, as well as hindering CO_2 mass transfer due to their high viscosity and the potential formation of hydrogen bonds [11].

3.2. Sorbent-Based Capture (Physisorption)

Physical adsorbents involve the attraction of CO_2 to pore walls through weak dipole interactions. Thus, all physical adsorbents have the inherent pitfalls of limited CO_2 capture capacity and selectivity, as physisorption isn’t as strong as chemisorption [8]. For all the carbon-based sorbents in this category, the general trend is that larger pore sizes (mesoporous carbons) correspond with easier diffusion of CO_2 and faster reaction kinetics, while smaller pore sizes (nanomaterials) increase surface area and adsorption capacity at the cost of reaction kinetics [15]. For the carbon nanomaterials analyzed in this study–graphene and carbon nanotubes–synthesis is very expensive. Researchers hope that their extreme durability, stability, and ability to survive many regenerations will make up for the upfront material cost in the long run [16]. The primary advantage of physical adsorbents is their low energy penalty; the heat capacity of solids is approximately four times lower than that of water, and physical adsorbents don’t have to expend energy on moisture evaporation during regeneration. Physical adsorbents also fare better than chemical adsorbents in this regard, as the lower heat of adsorption and the formation of weaker bonds reduces the energy requirements of regeneration [8].

3.2.1. Activated Carbons

Activated carbons (ACs) are derived from naturally occurring organic materials, typically chosen as adsorbents due to their irregular structure maximizing surface area and porosity. Because they come from common precursors, ACs are inexpensive, widely available, and very amenable to modification [11]. They also benefit from ease of transport and handling, simply by nature of being solid. They generally exhibit good regenerability, high thermal stability, low moisture sensitivity, and resistance to corrosion from the circulation of basic solutions [17]. However, despite their resistance to high temperatures, ACs have limited functionality under high pressures, have high friability, are sensitive to shifts in temperature, and underperform in the conventional 50-120˚C range [11]. ACs exhibit physisorption’s main drawbacks of low capture capacity and selectivity. These weaknesses can be mitigated with amine impregnation, but this comes with the drawbacks of heightening costs and decreasing microporosity–the backbone of physisorption [17].

3.2.2. Mesoporous Carbons

Mesoporous carbons are carbon-based adsorbents with uniform pore distribution and pore sizes in the mesoporous range (2-50 nm). In addition to having good customizability and regenerability, mesoporous carbons exhibit a greater adsorption capacity than ACs due to their pore structure–their pores being uniform and large is beneficial for rapid diffusion, thus bolstering the reaction kinetics and adsorption capacity of mesoporous carbons. In contrast to ACs, mesoporous carbons have limited efficacy under lower pressures as opposed to high pressures [18].

3.2.3. Graphene

Graphene is an allotrope of carbon, known for being an incredibly thin and strong nanomaterial, and its high surface area and hexagonal lattice structure make it a promising adsorbent for carbon capture. Graphene is well-suited for chemical surface modifications, increasing alkalinity and polarity which consequently increases adsorption capacity and selectivity [11]. Graphene has a strong pore structure featuring extremely narrow microporosity (<1 nm), maximizing surface area [19]. The sheer strength of the material helps it maintain structural integrity under high temperatures and pressures, as well as tolerating moisture [20]. Although small pore size typically indicates subpar adsorption kinetics, diffusion paths can be optimized during graphene synthesis to increase adsorption kinetics dramatically. The material's novelty and immense complexity of synthesis does present issues with affordability and scalability though, and graphene may not perform optimally when using real flue gas due to the water vapor and impurities present [19].

3.2.4. Carbon Nanotubes

Carbon nanotubes are another classification of carbon nanomaterials in the form of hollow, cylindrical tubes. They behave very similarly to graphene, demonstrating solid adsorption capacity, selectivity, customizability, and chemo-physical stability. The synthesis process is also costly because it is a nanomaterial, and an efficient regeneration process exists but it is complex to execute without error [9].

3.2.5. Zeolites

Zeolites are crystalline aluminosilicate minerals with uniform microporous structures that make them desirable for physisorption due to their pore structure providing high surface area. Naturally occurring zeolites exist and have a low cost, but exhibit low adsorption capacity, purity, selectivity, and efficacy at high temperatures (the adsorption reaction is exothermic, so the inability to handle heat is problematic). Synthetic zeolites, which are manufactured instead, fare better in these regards but are more expensive to produce. The production method of synthetic zeolites means they lend well to modification, such as altering their cationic composition to bolster selectivity [8]. Synthetic zeolites also exhibit good regenerability and adsorption capacity at high pressures. The main drawback of synthetic zeolites lies in the fact that they are very hydrophilic, requiring operation at high temperatures to limit the presence of moisture [11]. This thermal requirement comes at the cost of higher energy costs and compromising capture efficacy, as the capture ability of synthetic zeolites is noticeably lower at 120˚C compared to ambient temperatures [21]. Synthetic zeolites are also sensitive to flue gas impurities [20], as well as being prone to the destructive process of dealumination under the weak acidic conditions formed by a water and CO_2-rich environment [8].

3.2.6. Metal-Organic Frameworks

Metal-organic frameworks (MOFs) are porous materials composed of metallic clusters linked together by organic ligands. Their surface area is very high as a result of their porosity, allowing for high adsorption capacity–especially at high pressures [11]. Their surface properties and pore structures are easily modifiable, and they exhibit high selectivity and capture efficiency. This efficiency can be enhanced with sound-assisted fluidization, a power-intensive process that uses acoustic energy to increase particles' vibrational energy, optimizing the contact efficiency between CO_2 and the adsorbent [22]. While MOFs work excellently for capturing pure CO_2, their efficacy diminishes in practical settings due to limited regenerability, degradation at high temperatures, and instability when exposed to moisture and impurities in the flue stream. In addition, MOFs are expensive to produce because of the unique reagents required for their synthesis [8].

SORBENT-BASED CAPTURE (CHEMISORPTION)

3.3. Sorbent-Based Capture

Chemisorption involves the covalent bonding of CO_2 molecules to sites on the sorbent. As a result, these adsorbents exhibit a much higher heat of adsorption than physical adsorbents, resulting in greater CO_2 affinity and stronger bonds overall. However, this heightened adsorbent strength comes with drawbacks. For example, regeneration has much higher thermal demands, and chemical adsorbents have the tendency to form strong attractions with non-target molecules, reducing their available capture capacity and the sorbent's purity [8].

3.3.1. Amine-Impregnated Sorbents

Amine-impregnated sorbents are porous substrates that have been coated with amines, which noticeably increases the support material's adsorption capacity. Contrary to many other materials, amine-impregnated sorbents exhibit increased adsorption capacity at high temperatures, most likely due to the enhanced rate of CO_2 diffusion into the amine. Heat resistance is a beneficial trait because CO_2 adsorption is an exothermic process, although the energy required to establish hotter conditions can also be a drawback. Their capture also improves in the presence of moisture, as evidenced by the formation of carbonate and bicarbonate that occurs under hydrous conditions, but these improvements can backfire if moisture is too excessive. In addition to exhibiting large pore size and an inexpensive material cost, amine-impregnated sorbents also have versatile functionality for many types of support materials [11]. However, the impregnated amines also run the risk of limiting CO_2 transport to active sites, leaching over multiple regeneration cycles [8], and degrading due to low oxidative stability [20].

The potential bulkiness of surface amines can also lead to amine aggregation–as opposed to even dispersion, especially at lower temperatures where the amine can aggregate inside pores [11]. It's also worth noting that amine impregnation's benefits of low material cost and high CO_2 diffusion rates come with the caveats of complex optimal pre-processing and decreased adsorption kinetics, respectively [23].

3.3.2. Amine-Grafted Sorbents

Amine-grafted sorbents differ from amine-impregnated sorbents in that amines are covalently bonded to the sorbent material rather than physically held in place by van der Waals forces. As such, they demonstrate better durability and thermal stability during desorption than their amine-impregnated counterparts, and consequently have good cyclic performance [11]. They similarly boast low material cost, support versatility, and high adsorption capacity, while also suffering from low oxidative stability from amine degradation [20]. Researchers have identified sorbents, such as SBA-16, that are effective for amine grafting due to a hydrothermally stable cubic structure and high surface area availability for the grafting agent [24]. However, the grafted amines used to enhance the sorbent's adsorption capacity can also cause pore blocking, as well as being prone to deactivation due to urea formation that can occur under anhydrous conditions. The process of grafting amines through silylation can be quite complex as well, and amine protonation can occur throughout the process, requiring post-treatment to convert the protonated amine $-NH_3^+$ into the basic amino $-NH_2$ [11].

3.3.3. Metal Oxides

Metal oxides exhibit high adsorption capacity and speed for CCS, with their mechanical strength contributing to their stability during thermal decarbonation for desorption. They also benefit from accessibility, low cost, and amenability to modification [11]. Metal oxides like MgO demonstrate favorable thermodynamics due to the Gibbs-Helmholtz relationship, and their high surface reactivity allows them to enhance the active sites of other adsorbent materials such as ACs, as well as easily forming carbonate compounds upon contact with CO_2 [25]. However, regenerability has been shown to decay for metal oxides, such as CaO, due to a decrease in available surface area for carbonation. The synthesis and modifications needed to mitigate particle sintering can be complex, and fine-tuning factors such as morphology, crystallinity, and surface area for optimal performance can be difficult as well. Lithium-based metal oxides were also shown to be limited in practical applications despite their high adsorption capacity, due to their resistance to diffusion [11]. Materials such as MgO were shown to be promising, but the high temperatures required for optimal desorption (over 300°C) can be energy intensive. Across the board, metal oxides are excellent supplemental materials, but are limited when used in isolation. MgO alone is prone to sintering and formation of an impervious $MgCO_3$ layer to prevent adsorption, but shows more promise when used in conjunction with materials like green activated carbons [25].

3.4. Membrane-Based Capture

Membrane-based CO_2 capture takes advantage of the relative permeability of different gases when passed through a membrane to selectively separate the gases in the flue stream. As such, this method has the advantage of being a fairly simple operation because there are no chemical reactions, moving parts, or temperature swings involved. Membranes exhibit inertness to oxygen, and some exhibit high tolerance to wet acid gases as well. Membrane-based capture is fairly energy efficient in comparison to other materials discussed thus far, with an ability to capture approximately 90% of CO_2 while consuming only 20% of a plant's energy. The process is also advantageous for water conservation, as it doesn't require steam to operate and can even recover water from the flue stream [8]. Membranes' amenability to customization during synthesis allows for the optimization of efficiency, surface area, and tensile strength as well. Optimal synthesis can be quite complex, though, requiring a phase separation technique to prepare the membranes [26]. Membranes boast another theoretical benefit of flexibility in configuration due to their modularity, allowing them to be deployed in compact settings. In practice, however, a configuration that maximizes surface area is necessary to optimize adsorption capacity and permeability, which requires a large footprint. As such, the requisite capital costs to establish the infrastructure for efficient membrane-based capture can be quite costly. While membranes don't require utility steam, initiating the capture process does require significant pressure and vacuum capacity, and this supplemental power can demand additional cost. Membrane efficacy can be compromised by contaminants in the flue stream, such as SO_x and NO_x, ash, water, trace metals, H_2S, and NH_3 [8]. In the case of polymer-silica nanocomposite membranes, capture efficiency can be significantly improved with the addition of amino-SiO2 particles [26].

3.5. Direct Air Capture

Direct air capture involves the capture of CO_2 directly from the ambient atmosphere instead of capturing the CO_2 produced at point sources, thus allowing for theoretical negative emissions potential. Consequently, DAC systems aren't designed to be retrofitted, but instead require the construction of specialized DAC plants. Because the ambient air stream used for DAC has a significantly lower CO_2 concentration than that of flue gas, DAC systems undergo less sorbent degradation. However, the low CO_2 concentration and partial pressure in the gas stream also means that more circulation is required to capture adequate amounts of CO_2, which increases operational costs substantially. Compared to traditional negative emissions strategies such as reforestation, DAC can be deployed anywhere, not just arable land [27]. In addition, DAC plants take up a smaller land footprint in comparison to biological negative emissions strategies [28]. The construction of plants is expensive, though, requiring a significant initial capital investment as opposed to retrofitting existing plants with post-combustion capture or reforestation [27].

The consequences that come with large-scale construction projects, such as clearing land, extraction of raw materials, air pollution, and noise pollution, can be environmentally detrimental as well. A variety of sorbent options can be used in the capture process, with nanomaterials showing promise due to their high surface area and mobility in solution. While costly, nanocomposite materials overcome the hurdles of structural instability and high energy penalties for regeneration that other DAC sorbents face [29]. The primary drawback of direct air capture is that DAC plants don't produce their own energy and rely on external low-carbon energy sources, diverting away energy that could be utilized to displace centralized carbon sources in the process [28].

DAC has additional resource impacts, especially in water use; Solvent DAC systems can consume between 1-7 tonnes of water per ton of CO_2 per tonne of CO_2 captured [30], which is a similar rate of water consumption that cement and steel plants use per tonne of material production [31]. Solid sorbent DAC systems typically have high water consumption rates as well, at 1.6 tonnes of water relative to tonnes of captured CO_2 [32], although low temperature solid sorbent-based DAC systems show promise due to having no reliance of external water whatsoever [33]. The scientific consensus regarding DAC's role in counteracting climate change is that reliance on prospective DAC technologies can heavily skew overshoot trajectories in CO_2 emissions models, and caution must be taken as to avoid overly optimistic assumptions in DAC's ability to counteract extraneous carbon emissions. However, DAC is also acknowledged as necessary in order to truly achieve net zero emissions, especially to neutralize emissions from select sectors that are notoriously difficult to decarbonize–namely the cement, steel, chemical, ship, and plane manufacturing industries [28].

Table 1: Qualitative descriptions of post-combustion and direct air capture materials

Method/Material	Advantages	Disadvantages
Aqueous Amines-MEA [34]	● Commercialized and used for decades in other industries [11] ● Biodegradable [11] ● Fast reaction kinetics [11] ● Low volatility [11] ● Thermal and oxidation degradation resistant [11] ● Energy efficient [11] ● Low viscosity and corrosion [8] ● Low cost of capture process [34]	● Low loading capacity [11] ● Degradation due to impurities and other gases in the flue stream [11] ● Large equipment required [11] ● Energy penalty during regeneration for moisture evaporation [8] ● Working capacity and circulation hindered due to water content [8] ● Water content requires more maintenance [8] ● Regeneration is energy-intensive and expensive [34]
Non-Aqueous Amines-MAE/EGBE [13]	● Low heat requirements for regeneration [8] ● Thermal degradation resistant [8] ● Low buildup of heat-stable salts under SOx and NOx exposure [8] ● 30% lower circulation required than MEA [8] ● Cheaper regeneration than MEA [8]	● Lower cyclic capacity than aqueous counterparts [13] ● Poor mass transfer due to high viscosity [13] ● Can react with CO2 to form unstable carbamates and protonated amines [13]
Phase Change Solvents and Ionic Liquids-[TETA]Br + PMDETA+H_2O [14]	● Minimal solvent loss to evaporation [11] ● High polarity [11] ● Versatility in absorption [11] ● High regeneration efficiency [14] ● High capture capacity due to low equilibrium pressure [8]	● Poor mass transfer due to high viscosity [11] ● Hydrogen bond formation in ILs containing amino-functional groups [11] ● Complex and expensive synthesis of TETA with acids [14] ● Requires slurry filtration after absorption [8] ● Requires novel contactors [8]
Activated Carbons- Palm fiber [35]	● Precursor availability [11] ● Low cost [11] ● High thermal stability [11] ● Tolerant to moisture [11] ● Modifiability [8] ● High surface area and porosity [20] ● Transportability and handleability [17]	● Limited functionality at high pressures and the conventional 50-120˚C range [11] ● Sensitive to shifts in temperature [11] ● Low capture capacity and selectivity [11] ● Friability [20] ● Amine impregnation decreases microporosity [17]

Method/Material	Advantages	Disadvantages
	● Doesn’t corrode from basic solutions [17] ● Can enhance selectivity with amine impregnation [17]	
Mesoporous Carbons- Ordered Mesoporous Carbons [18]	● Reasonable adsorption capacity [11] ● High surface area and porosity [11] ● Modifiability [8] ● Easy regenerability [8] ● Synthesis is nontoxic and affordable [18]	● Limited selectivity [8] ● Limited efficacy at lower pressures [18]
Graphene- Nitrogen-Doped Porous Carbons Derived from Graphene [19]	● Reasonable adsorption capacity [11] ● Modifiability [[8] ● High chemo-physical stability [20] ● Tolerant to moisture [20] ● High surface area and porosity [19] ● High surface polarity due to nitrogen doping [19] ● Fast adsorption kinetics [19] ● High selectivity [19] ● High alkalinity due to KOH and urea treatment [19]	● Expensive synthesis [20] ● Difficult scalability [19] ● Instability with water vapor and impurities [19]
Carbon Nanotubes- Carbon Nanotubes with 3-aminopropyl-triethoxysilane [9]	● Reasonable selectivity [11] ● Modifiability8 ● High chemo-physical stability [20] ● Tolerant to moisture [20] ● High surface area and porosity [9] ● Reasonable adsorption capacity due to APTS enhancement [9]	● Expensive synthesis [20] ● Difficult regeneration [9]
Zeolites- 13X [21]	● High surface area and porosity [11] ● Chemical modifiability [11] ● Can mitigate low selectivity by altering cationic composition [8] ● High regenerability [8] ● High adsorption capacity at high pressures [21]	● Low selectivity [11] ● Very hydrophilic [11] ● Potential dealumination in weak acidic conditions [8] ● Difficult regeneration [8] ● Sensitive to impurities [20] ● Expensive synthesis [20] ● Limited efficacy at higher temperatures [21]
MOFs- HKUST-1 [22]	● High surface area [11] ● High adsorption capacity at high pressures [11] ● High selectivity [22] ● Modifiability [22] ● High efficiency due to sound-assisted fluidization [22]	● Instability with water vapor and impurities [20] ● Expensive synthesis [8] ● Degradation at high temperatures [8] ● Limited regenerability [22] ● Sound-assisted fluidization is energy intensive [22]
Amine-impregnated Sorbents- AlFu with TEPA [23]	● High adsorption capacity due to amine impregnation [11] ● High diffusion rate at high temperatures [11] ● Higher capture in the presence of moisture [11] ● Versatility of supports [11] ● High porosity [11] ● Stable cyclic performance [11] ● Cheap production cost [20]	● Surface amines can aggregate [11] ● Limited functionality at low temperature due to polyethylenimine formation in pores [11] ● Amines limit CO_2 transport to active sites [8] ● Amines leach over multiple regeneration cycles [8] ● Degradation due to oxidative instability [20] ● Adsorption kinetics decrease with amine loading [23] ● Expensive synthesis and pre-processing [23]
Amine-grafted Sorbents- SBA-16 [24]	● High thermal stability during regeneration [11] ● Durability due to strong covalent grafting of amines [11] ● Modifiability [11] ● High cyclic performance [11]	● Complex synthesis [11] ● Amine deactivation due to urea formation [11] ● Amine protonation can occur during synthesis [11] ● Grafted amines can block pores [11]

Method/Material	Advantages	Disadvantages
	● Versatility of supports [20] ● Cheap production cost [20] ● High adsorption capacity and surface area due to fine sorbent particle size [24] ● SBA-16 has a hydrothermally stable cubic cage structure [24]	● Degradation due to oxidative instability [20]
Metal Oxides-MgO [25]	● High adsorption capacity and speed [11] ● Mechanical strength [11] ● Accessibility and low cost [11] ● Can be desorbed with thermal decarbonation [11] ● Modifiability [11] ● High surface reactivity and surface area [25] ● Reaction has favorable enthalpy [25] ● Can bolster other adsorbents' performance [25] ● Forms carbonate compounds upon contact with CO_2 [25]	● Limited regenerability [11] ● Complex synthesis [11] ● Limited desorption efficacy at ambient temperatures [25] ● Performance depends on synthesis fine tuning [25] ● Limited efficiency due to the formation of an impervious MgCO3 layer [25]
Membrane-based-PVDF-HFP-40 wt% AFS [26]	● Simple operating process [8] ● Exhibits high tolerance to wet acid gases and inertness to oxygen [8] ● Scalability due to membrane modularity [8] ● Energy efficient [8] ● Can recover water from flue gas [8] ● No steam requirement [8] ● High efficiency, surface area, and tensile strength due to amine modification [26] ● Modifiability [26]	● Requires large infrastructure to counteract limited permeability [8] ● High capital costs for infrastructure and adequate membrane coverage [8] ● Compression and vacuum capacity required to initiate the capture process [8] ● Sensitive to impurities [8] ● Efficacy may depend on surface area and particle quantity of amino-silica particles [26] ● Complex synthesis [26]
Direct Air Capture-50%PEI/SBA-15 [29]	● Theoretical negative emissions potential [27] ● Low sorbent degradation [27] ● Various viable sorbent options [27] ● High surface area and mobility in solution when using nanomaterials [29] ● Necessary to truly achieve net zero emissions [28] ● More deployment flexibility and smaller land footprint than biological negative emissions strategies [28]	● High circulation costs due to low CO_2 concentrations [27] ● Construction of DAC plants is extremely expensive and environmentally costly [27] ● Will consume much of the renewable energy supply [28] ● Can skew overshoot trajectories for CO_2 emissions models [28] ● Solvent-based DAC can use 1-7 tonnes of water per tonne CO_2 captured [30] ● Solid sorbent-based DAC can use 1.6 tonnes of water per tonne CO_2 captured [32] ● Low adsorption capacity due to low partial pressure of CO_2 in the flue stream [29] ● Most sorbents are structurally unstable and energy-intensive during regeneration [29] ● Nanomaterials are more stable but costly [29]

Table 2: Carbon capture efficiency, CO_2 flue concentration, TRL, and optimal operating temperature of post-combustion and direct air capture materials

CCS Technology			**Carbon capture efficiency [mmol CO_2 / g material]**	**Flue Concentration of CO_2 [%]**	**TRL**	**Optimal operating temperature [°C]**
Solvent-Based Capture		Aqueous Amines- MEA [34]	0.479 mmol / g	10-13%	9	30°C
		Non-Aqueous Amines- MAE/EGBE [13]	2.148 mmol / g	20%	4	40°C
		Phase Change Solvents and Ionic Liquids- [TETA]Br + PMDETA+H_2O [14]	4.90 mmol / g	100%	4	30°C
Sorbent-Based Capture	Physisorption	Activated Carbons- Palm fiber [35]	1.84 mmol / g	100%	6	25°C
		Mesoporous Carbons- Ordered Mesoporous Carbons [18]	1.50 mmol / g	100%	4	25˚C
		Graphene- Nitrogen-Doped Porous Carbons Derived from Graphene [19]	3.24 mmol /g	100%	3	0°C
		Carbon Nanotubes- Carbon Nanotubes with 3-aminopropyl-triethoxysilane [9]	2.59 mmol / g	50%	4	20˚C
		Zeolites- 13X [21]	0.70 mmol / g	15%	4	120°C
		MOFs- HKUST-1 [22]	1.14 mmol / g	15%	4	25˚C
	Chemisorption	Amine-impregnated Sorbents- AlFu with TEPA [23]	4.10 mmol / g	100%	3-4	75°C
		Amine-grafted Sorbents- SBA-16 [24]	0.727 mmol / g	15%	4	60°C
		Metal Oxides- MgO [25]	0.571 mmol / g	5%	4	40°C
Membrane-Based Capture		Membrane-based- PVDF-HFP-40 wt% AFS [26]	0.767 mmol / g	100%	4	50°C
Direct Air Capture		Direct Air Capture with Nanomaterials- 50%PEI/SBA-15 [29]	1.3 mmol / g	0.04%	3	25°C

4. DISCUSSION

Each category of carbon capture analyzed in this paper offers unique advantages and drawbacks in addressing CO_2 emissions. Solvent-based capture leverages liquid solvents for CO_2 absorption, but faces a tradeoff between solvent viscosity and thermal regeneration efficiency. Sorbent-based capture can be divided into physisorption and chemisorption. Physisorption involves weaker dipole interactions and benefits from low energy requirements for regeneration, but has limited CO_2 capacity. Conversely, chemisorption forms strong covalent bonds, offering high CO_2 affinity, but requires substantial thermal energy for regeneration. Membrane-based capture utilizes selective gas permeability, is energy-efficient and advantageous for water conservation, but requires significant capital investment and auxiliary power to run. Direct air capture targets CO_2 directly from the atmosphere, allowing theoretical negative emissions and is thus considered essential for truly achieving net zero emissions. However, DAC faces high operational costs due to the low CO_2 concentration in ambient air, as well as requiring substantial initial capital investment for plant construction.

The inherent tradeoffs observed for every material indicate that there is no approach that is unequivocally superior for comparing current CCS technologies and their implementation methods, in terms of the factors analyzed in this study.

The need for further development of CCS technology to counteract climate change in accordance with the Paris Climate Agreement is clear [36], and this is supported by the findings that many of the CCS technologies in laboratory stages of development (i.e. the lowest TRLs) show the most promise. The two materials with the highest TRLs in context—aqueous amines and activated carbons—exhibited significant disadvantages of inefficient regeneration and friability respectively that the more novel materials in the same category didn't suffer from.

4.1. Limitations and Challenges

The scope of this study in comprehensively comparing the selected CCS technologies is limited due to the potential confounding of variables when numerically comparing the viability of these materials. This includes the effects of the partial pressure and concentration of CO_2 in the flue stream used in testing each material, as well as the effects on operating temperature on energy consumption. This research challenge was exacerbated by a lack of information being reported in experimental research within this field. For example, when determining the influence of several extraneous factors on the capture performance of activated carbons, García et al found that "the CO_2 partial pressure was the most influential variable on both the CO_2 capture capacity and the breakthrough time during the capture process" [37]. However, in the case studies analyzed for this paper, the partial pressure of CO_2 of the flue stream used in each respective study was not reported a majority of the time. Similarly, Hsu *et al.*,'s experimentation when testing the performance of CNTs confirmed that the CO_2 flue concentration used in testing directly relates to the experimentally determinable adsorption capacity [9]. Despite this, we encountered comparison papers similar to this one that omitted this statistic when directly comparing various CCS materials, even though the flue concentration of CO_2 was not standard across the case studies analyzed in these papers.

The lack of standardization when reporting experimental data posed the most direct challenge to the credibility of our results, and we believe future research should prioritize transparency in recording all potential lurking variables when collecting performance data, for the sake of comparison. Another limitation of this study was the lack of documentation of the longevity of many of the selected technologies, such as a life cycle analysis. Thus, it was difficult to gauge the practical efficacy of the more novel technologies outside of a laboratory setting, which is why we believe more thorough research should be performed for the newer technologies analyzed in this paper.

4.2. Future Directions of CCS

Despite the promise that many novel CCS materials have demonstrated, it's crucial to note that CCS cannot be used as justification to keep all fossil fuel plants in operation or as an alternative to transitioning away from oil and gas. The IEA's roadmap to net zero emissions (NZE) by 2050 supports this claim. For example, although the IEA's NZE scenario accounts for CCS capturing 6 billion tons of CO_2 by 2050, it primarily uses CCS to decarbonize the select few sectors where reducing emissions is the least feasible—namely the cement, steel, chemical, ship, and plane manufacturing industries. The NZE scenario instead primarily focuses on the growth of renewable energy, projecting renewable energy to account for nearly 90% of electricity production by 2050 in order to achieve net zero [38]. This strategy would be economically feasible, as within the 2010s decade, the cost of photovoltaic solar power fell 85%, with onshore and offshore wind costs dropping almost 56% and 48% respectively [39]. In contrast, researchers at the Oxford Smith School of Enterprise and the Environment compared a low-CCS and a high-CCS net zero plan—using CCS to neutralize 10% and 50% of carbon emissions respectively—and estimated that the high-CCS route would cost about $30 trillion more in comparison by 2050 [40]. Also, while not the focus of this paper, it's important to note the limitations in storing captured carbon; with a leakage rate of 0.1% annually, the leakage of sequestered carbon can result in 25 Gt of CO_2 in additional emissions, as well as potential health risks and extra costs that must be accounted for [41]. While the development of CCS is essential in the plan to counteract global warming, it is imperative that CCS technologies—especially DAC—should not be used as compensating strategies to delay or hinder the pursuit of more urgent solutions, such as transitioning to an infrastructure based on renewable energy [28].

5. CONCLUSION

This study highlights the necessity of advancing CCS technologies to address CO_2 emissions in accordance with the Paris Climate Agreement, as well as the limitations of existing and emerging materials. Among the CCS methods of solvent-based capture, sorbent-based capture, membrane-based capture, and DAC, no single technology currently stands out as the definitive "best" solution. Several approaches in early development show significant promise, but more research is necessary to overcome limitations such as regeneration inefficiencies and operational costs. We also identify challenges in standardizing experimental data within this field, with crucial variables such as flue concentration of CO_2 often being omitted from literature and resulting in difficulty when holistically comparing technologies. The IEA also emphasizes that CCS should primarily be used as a supplementary strategy to target hard-to-decarbonize sectors, with renewable energy as the primary focus of the pathway to net zero—especially when considering the pitfalls of carbon sequestration. In conclusion, further research and development, as well as standardized reporting and comprehensive life cycle analyses, are crucial for optimizing the effectiveness of CCS in combating global climate change.

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