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Current Opinion in
Green and Sustainable Chemistry

Recent advancements and challenges in carbon capture, utilization and storage

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Abstract

This short paper suggests a review of the latest developments and current challenges associated with carbon dioxide capture, utilization and storage. Recent research has been conducted to reduce energy consumption, costs, and improve efficiency. In carbon dioxide capture, catalysts have been added to solvents while new membranes and sorbent materials have been investigated. In mineral carbon dioxide storage, studies have been carried out to improve reaction rates. Regarding the utilization path, attention has been focused on the development of sustainable chemicals (mainly based on electrochemical conversion), biochemical routes and power generation. Considering the respective challenges, future efforts should be focused toward the optimization of these systems at all levels, in addition to a public acceptance and new policies and regulations for their spread.

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Current Opinion in Green and Sustainable Chemistry 2024, **46:**100895

This review comes from a themed issue on **Chemistry for Climate (2024)**

Edited by **Borhane Mahjoub**

Available online 13 February 2024

For complete overview of the section, please refer the article collection - Chemistry for Climate (2024)

https://doi.org/10.1016/j.cogsc.2024.100895

Keywords
Carbon dioxide, Carbon dioxide capture technologies, Carbon dioxide conversion, Carbon dioxide storage, Developments, Challenges.

Introduction

Today, the impacts of climate change and global warming are being experienced everywhere and these are the most important concerns recognized by world leaders and experts in the 24th annual UN Climate Change Conference that took place in Poland in 2018 [1].

It has been demonstrated that these phenomena are caused primarily by the un-controlled emissions of carbon dioxide (CO_2) from the industrial sector and distributed sources, contributing to about 71.6% of the overall amount of greenhouse gases. CO_2, in fact, absorbing and trapping heat, causes the Earth's temperature to rise. The only solution to this environmental problem is the reduction of both CO_2 emissions and concentration in the atmosphere. Urgent actions are needed: it has been estimated, in fact, that without an effective intervention, net CO_2 emissions could reach a value of 48–55 Gton/year by 2050, due primarily to the increase of future energy demands [2]. Consequently, the atmospheric CO_2 concentration is expected to increase and, in the absence of mitigation, its concentration is projected to double by 2100 compared to the current level of 424 ppm, so that the global mean temperature could increase by up to 6.1 °C compared to the 1990 level, a value much higher than the target (1.5 °C) established in the COP21 [3,4].

The scientific community agrees that solutions aiming at CO_2 mitigation and removal from the atmosphere are required worldwide to change the direction: a 45% and 100% reduction in anthropogenic CO_2 emissions by 2030 and 2050 has been respectively proposed [5].

To achieve these objectives at a global scale and establish a low-carbon economy, technologies for CO_2 capture from a point source or the atmosphere, storage and utilization have been deeply analyzed in the literature and experimented by the most important companies [6–8]. There are different reviews in the literature about CO_2 storage, utilization and capture but a comprehensive work about recent developments (last two years), challenges and future research is missing and for this reason the proposed work wants to fill this gap.

Recent advancements in carbon capture, utilization, and storage

CO_2 capture

Chemical and physical absorption, adsorption, membrane separation, cryogenic processing and chemical looping combustion are the principal technologies to extract CO_2 from flue gases, with characteristics shown in Table 1 [9,10]. However, due to their important role, a continuous research is carried out, so that hybrid technologies, such as a combination of the above, are rapidly evolving as alternative options to reduce costs and energy requirements [11]. Other advances for CO_2 capture from exhaust streams include ionic liquids, nanofluids, microencapsulation, phenoxide salts, enzymes, membranes and sorbents [12,13].

Table 1

Main CO_2 separation methods and their advantages [8,42].

Technology	Mechanism	Advantages
Physical absorption	Absorption due to the solubility of CO_2 in the solvent governed by Henry's law; the solubility changes with pressure or temperature.	a) 90% of CO_2 separation efficiency b) Low energy consumption for sorbent regeneration c) Temperature required for the process is lower than that for chemical methods d) Low corrosivity and toxicity e) More economical at a higher CO_2 partial pressure
Chemical absorption	CO_2 chemically reacts with the solvent to form unstable salts; upon heating, CO_2 is released.	a) Most mature technology b) Simplicity and the possibility of using it with a low CO_2 partial pressure c) Suitable for retrofit d) High absorption capacities e) Product purity >99% vol
Adsorption	CO_2 separation in mixed-gas streams by solid-material adsorption; changes of temperature and pressure to achieve CO_2 desorption.	a) 85% of CO_2 separation efficiency b) Ease of use and maintainability of the installation c) Since adsorbents can be reused, low waste generation d) Reversible process (physical adsorption) e) Large selection of materials with high CO_2 uptake f) Low energy requirement to regenerate an adsorbent material g) Wide operability range h) Possibility to use waste biomass or industrial resides as raw materials for the adsorbent synthesis
Membrane	CO_2 from a main stream is separated by using a membrane which acts like filter having a selective permeability.	a) 80% of CO_2 separation efficiency b) Uncomplicated process c) No regeneration energy is required d) Simple modular system e) No waste streams f) Higher separation energy efficiency compared to that of absorption and adsorption g) No additional chemicals in the separation process
Cryogenic distillation	Consecutive refrigeration at different condensation temperatures with the condensation of gas mixture to separate CO_2	a) High CO_2 purity b) High separation efficiency (up to 99.9% vol. CO_2) c) Production of ready to transport, pure liquid CO_2 d) No need of chemical reagents e) Suitable for high pressure gas stream with high concentration (>50%vol.) f) Easy scaled-up to industrial application
Calcium looping	CO_2 capture occurs through reversible reactions between CaO and CO_2	a) Cheap raw materials for sorbent synthesis b) Optimal method for retrofit of pulverized coal-fired power plants and sorption-enhanced hydrogen production process
Chemical looping combustion	The combustion is divided into intermediate oxidation and reduction processes that are carried out independently, with a solid oxygen carrier moving between the two separated units. The oxygen carrier is first oxidized with air forming an oxide. This oxide is then reduced using a hydrocarbon as a reducer in a second reaction, where CO_2 and H_2O are released.	a) Simplicity and the possibility of using it with a low CO_2 partial pressure b) The exhaust gas from the air reactor is mainly N_2 c) The exhaust gas stream from the fuel reactor is composed of CO_2 and H_2O (CO_2 can be easily separated by a condenser) d) Avoids huge energy penalty and thus less operational costs

Through the use of ionic liquids, it is expected to improve the capture efficiency and reduce the energy required for solvent regeneration [14]. These particular solvents, in fact, are less susceptible to degradation and impurities. On the other hand, the addition of nanoparticles (e.g. SiO_2 or carbon nanotubes) to a solvent, microencapsulation, and phenoxide salts have been suggested as strategies to improve the absorption performances in terms of stability, energy and capture efficiency, and even costs [13,15]. An additional and interesting research area is the use of new type of carbonic anhydrase enzymes as catalysts (free or immobilized on different supports) dispersed in the liquid phase which may have energetic and economic advantages compared to the traditional monoethanolamine based solvent and membrane contactors [16].

Several studies have been conducted to find an advanced material for membranes (e.g. polymer, ceramic, composite metals, Metal Organic Frameworks (MOFs), zeolites, mixed matrix, graphene oxide, polyimide) characterized by a good selectivity toward CO_2, low energy consumption, reduced space requirements [7,12,17]. In addition, the doping of membranes with ionic liquids and nanoparticles is under investigation [18].

New physical sorbents have been investigated and considered highly promising such as carbon nanotubes or multi-wall carbon nanotubes, carbon dots, graphite oxide, MOFs, porous carbons, porous organic polymers, and covalent organic frameworks [5,19]. In addition to their synthesis, the advances have been directed to implement these discoveries aiming to improve capture capacity and long-term stability/durability [17]. In recent studies, process configurations have been also suggested: CO_2 capture via CaO sorbent has been integrated into utilization to produce syngas [20] and recycled methane [21].

Regarding CO_2 capture from the air, the most investigated and mature technologies are the absorption or adsorption that are adopted by the main companies as shown in Table 2 [22]. Studies are currently also carried out for membrane and electrochemical based technologies [12,17]. Regarding adsorption, materials with good CO_2 adsorption capacities and low regeneration energy have been investigated: MOFs [23], amine functionalized sorbents [24], zeolites [25], carbon-based materials [26], porous organic polymers [27], porous covalent organic frameworks [28], silica and silica-amine based sorbents, hybrid ultra microporous materials, biochar, and metal oxide-based sorbents [17]. Innovative membrane materials to improve the selectivity are currently under research: mixed matrix membranes [29], supported ionic liquid membranes [30], MOF membranes [17]. Current findings of synthetic strategies for several functional and redox-active organic sorbents with good CO_2 selectivity, solvent stability, electrode design, and defined physical properties are under investigation for the electrochemical capture route [31]. For the absorption system, amino acid and peptide salt solutions have been proposed due to a good resistance toward thermal degradation and oxidation, low corrosivity and toxicity, fast CO_2 reaction rates [17].

CO_2 storage

CO_2 storage technologies commonly include geological, mineral carbonation, terrestrial and ocean storage options as analyzed in Table 3. Among them, electrochemical, microbial, and supercritical CO_2 mineralization storages are the latest advancements in this subarea with the aim to accelerate reaction rates and reduce energy consumption [12]. Ongoing research in biochar production and soil amendments is under development to increase the efficiency of terrestrial storage potentially able to permanently remove from the air 2.879 ton CO_{2eq} per ton of dry biochar [12,32]. Ocean fertilization, artificial upwelling, ocean alkalinity enhancement, and marine permaculture are currently under investigation to increase efficiency and sustainability in the ocean storage technique [12].

CO_2 utilization

Recent studies on CO_2 utilization are about the development of new processes mainly exploiting renewable energies with a minimal carbon footprint. One of these processes is based on the CO_2 electrochemical reduction to valuable compounds (e.g. formic acid, propanol, methanol, ethylene, methane) driven by renewable electricity [33]. The development of efficient electrocatalysts is a research frontier today: carbon-based materials including metal-free carbon and metal-based carbon catalysts have shown great potential, due to the tunable porous structures, abundance in nature, resistance to acids, bases and high-temperatures, and environmentally friendly feature [34]. In particular, numerous discoveries in the design, synthesis, characterization, and deployment of Cu-based materials have been proposed by Ahmad et al. [35].

An alternative to electricity is the sunlight which can be used for CO_2 photochemical reduction, recently proposed and analyzed to understand its operating principles [12].

Another utilization technology under investigation is the non-thermal plasma and new types of plasma

Table 2

Comparison of the current and future planned (*) DAC plants around the world [45] (The * symbol indicates future planned. The N/A stands for not available).

Company (plant type)	Location and country	Sorbent type	Regeneration temperature (°C)	CO_2 removal capacity (tonCO_2/year)	Thermal energy (GJ/tonCO_2)
Carbon Engineering (pilot)	British Columbia, Canada	Liquid	900	350	8
Carbon Engineering* (commercial)	Texas, USA	Liquid	900	1000000	N/A
Climeworks (pilot)	Zurich, Switzerland	Solid	80–100	900	7
Climeworks (commercial)	Hellisheidi, Iceland	Solid	80–100	4000	N/A
Climeworks (pilot/commercial)	Europe	Solid	80–100	2000	N/A
Global Thermostat* (commercial)	Oklahoma, USA	Liquid	100–120	4000	N/A
Infinitree LLC	New York, USA	Solid (Ion exchange)	Humidity Swing	100	N/A

Table 3

Comparison and summary of different carbon storage technologies [12].

Technology	Advantages	Development stage	Future Outlook
Geological storage	-Proven technology -Large storage capacity	-Mature -With commercial-scale projects ongoing	Expected to grow in importance, particularly for large scale CO_2 emitters and industries
Mineral carbonation storage	-Permanent storage -Potentially used in construction materials -Utilizes waste materials	-Early stage -With some pilot projects	Promising, but requires advancements in technology and cost reduction for a wider implementation
Terrestrial storage	-Multiple co-benefits -Enhances ecosystem services -Supports biodiversity	-Mature -With widespread adoption and research	Positive outlook, with growing interest and support from the governments, industries and communities
Ocean storage	-Large storage capacity -Potential for long term storage	-Early stage -With limited implementation	Uncertain, depends on advancements in research, regulatory frameworks, environmental concerns

generation have been investigated: dielectric barrier, microwave, corona, radio frequency, glow, and nanosecond pulse discharge options [36].

New achievements have been also obtained in the agriculture sector where CO_2 can be used to increase the efficiency of photosynthesis for algae (converted into biofuels and other bio-products) and crop cultivations [12]. Continuous efforts have been devoted to optimize algae culture conditions, design and optimize novel photobioreactor [37]. In addition, genetic engineering, synthetic biology methods and co-cultivation of algae with other microorganisms are constantly improving [38].

Similarly, in the biological CO_2 conversion, genetic engineering techniques are under investigation to improve the metabolic pathways of microbes in addition to new microbial electro-synthesis routes [39].

Another interesting CO_2 utilization route is for power production, energy storage, cooling and direct air capture (DAC) based on using geothermal energy [21].

Challenges in carbon capture, utilization, and storage

CO_2 capture

Different obstacles should be overcome in order to increase the deployment of CO_2 capture technologies. Generally, further development effort should be conducted with the aim to reduce costs and energy consumptions while increasing the capture efficiency. Table 4 shows some key challenges for technologies capturing physically or chemically CO_2 from a flue gas [40].

As the latest proposed capture technology, DAC has to face high costs (for energy and materials) to move a large amount of air and scalability at a large scale for commercialization [41]. Also, capture mechanism and kinetics inside a material, more tuning and tailoring of materials to improve efficiency, are needed to be understood [42].

Overall, the development of stable, scalable, and environmentally friendly materials (solvents and sorbents) and processes for CO_2 capture will increase social and political acceptances for a large-scale implementation [6].

CO_2 storage

The most common challenges that must be addressed and considered for CO_2 storage to improve the efficiency are leakage, long-term safety, economic and government laws or costs, good site selection (e.g. geological heterogeneity affects microscopic fluid displacement, caprock integrity, induced seismicity and CO_2 injectivity), effective monitoring of storage cavity and the surface site, public acceptance [6,21]. Small valve failures, larger faults in containers, caprock failures can cause leakages that can contaminate the groundwater with negative effects [42]. Technologies for pressure management and seals are important to be developed [43].

It should be also underlined that terrestrial storage depends on land availability and management practices, mineral carbonation is energy-intensive while ocean storage is at the early stages of development [12].

CO_2 utilization

More studies must be done to overcome limits in different technologies. A main common challenge is the cost [42], while others could be found for each utilization technology [12]. In the electrochemical reduction, efficient and selective catalysts as well as a high energy input are required. Much research is still required to understand the catalyst's working

Table 4

Challenges for CO_2 capture technologies from flue gas [40].

Technology	Material	Challenges
Physically		
Membrane		-Low concentration of CO_2 in the fuel gas leads to a higher energy consumption -Sensitivity to moisture (i.e., lower selectivity). -The high temperature of the flue gas degrades organic membranes. The gas must be cooled below 100 °C. -Membranes must be resistant to flue gas impurities, aging and plasticization (hardening). -Single-stage membrane systems are not capable of high CO_2 capture efficiency; a second stage is required. -The low concentration of CO_2 in the fuel gas leads to a high separation energy and the need for membranes with a high selectivity. Therefore, it is not economical in terms of scale. -Trade-off between permeability and selectivity in polymeric membranes. - Water condensation on membrane and decrease of selectivity and permeance when the flue gas has NOx and SOx passing through the membrane.
Adsorption	Zeolite	-The presence of impurities (NOx, SOx and H_2O) significantly affects performances. -It is time and energy consuming for the complete regeneration as a temperature swing approach is required.
	MOF	-Negatively affected by NOx, SOx, and H_2O. -Low CO_2 selectivity in carbon dioxide/nitrogen gas streams. -Lack of experimental data on performances after multiple adsorption/desorption cycles. -Pressure and temperature swing desorption approaches have not been adequately investigated. -By increasing the porosity of MOFs, their mechanical stability is compromised. -The instability of MOFs may cause a phase change in them. -The cost of CO_2 capture through MOFs is high.
Cryogenic distillation		-The water content of the feed stream must be removed to avoid equipment clogging due to the ice formation. -Building up of solid CO_2 reduces the efficiency of the evaporator over time. -High capital costs of equipment. -High costs of the refrigerant used to cool the system.
Absorption	Selexol process	-Process is the most efficient at elevated pressures. - Solvent regeneration needs to be conducted at a lower temperature that is currently used to avoid any reduction in the solvent.
	Rectisol process	-The solvent is capable of absorbing trace metal compounds, such as mercury to form amalgams at low operating temperatures. -Solvent cooling leads to high operating costs. -Complex operating scheme leads to high capital costs. - Solvent regeneration needs to be conducted at a lower temperature that is currently used to avoid any reduction in the solvent.
	Fluor process	-High solvent circulation rates (increasing operating costs). -High solvent costs. - Solvent regeneration needs to be conducted at a lower temperature that is currently used to avoid any reduction in the solvent.
Chemically		
Absorption		-High energy requirements. -The limited CO_2 absorbing capacity is caused by the reaction stoichiometry and depends on the absorbent type. -Requires a regeneration step.
	Amine	-Low CO_2 loading capacity of the solvent. -Amine degradation in the presence of nitrogen oxides, sulfur oxides, O_2, and particulate matter. -Corrosion in amine equipment causes absorption column and stripper components to degrade over time. -The solvent cannot be completely regenerated. -The recovery step is energy intensive and the waste stream can be hazardous. -Higher water consumption than other carbon capture processes. -Potential for toxic emissions to the environment in the form of amine and amine derivative products due to the solvent degradation.
Adsorption		-Adsorbent degradation in cyclic operations. -Possible decrease in the adsorption capacity of adsorbent after the desorption step. -Cyclic process requires regeneration.

(*continued on next page*)

Table 4 (*continued*)

Technology	Material	Challenges
	Activated carbon	-Low CO_2 capacity in mild conditions. -The wide variety of raw materials means that a wide range of pore characteristics is often seen between adsorbents. -Negatively affected by NOx, SOx, and water
Calcium looping		-Rapid decrease of limestone (sorbent) capacity after several cycles of reaction with CO_2. -Environmental concerns due to the limestone mining, wastes from Ca-looping (i.e., spent calcium oxide (CaO)) and the need for high temperatures for the operation. -Need for an air separation unit to obtain pure oxygen for calcination.
Chemical looping combustion		-High oxygen production costs. -High sensitivity to the air leakage in the system. -It is difficult to retrofit. -Special materials are needed to resist the high flame temperature (ca. 3500 °C).

mechanism, morphological variations, degradation mechanism during electrocatalysis, nature and number of active sites of the catalysts through in situ and operando spectroscopic and microscopic methods [34,35]. The use of hydrogen as a reductant is also popular but depends on abundant, low-cost, low-carbon hydrogen.

Photochemical reduction is still characterized by limited efficiency, photo-catalyst activity concerns, and scalability. Moreover, more advanced photocatalysts and light-harvesting materials should be proposed. Obstacles are present for the development of plasma-based conversion due to the high energy consumption and low selectivity. In the agricultural sector, CO_2 enrichment in greenhouses or large-scale algae cultivation, needs important investments in infrastructure and technology, becoming challenging for small-scale farmers or in developed countries [44]. Also, in biological conversion processes, the growth rate of microorganisms is slow, the separation and purification sections need to be improved and the genetic engineering is complex.

Moreover, public acceptance, regulatory approval and intellectual property issues have to be considered when genetic modifications occur.

Conclusions and outlook

In this work, the latest advancements and challenges for CO_2 capture, utilization, and storage are reported.

Although recent studies improving performances of CO_2 capture, storage and utilization technologies, there are technical (mainly a high capital cost, energy penalty and low efficiency) and non-technical (public awareness and perception, lack of economic subsidies, and bad government regulation for storage and transit) development obstacles.

In the future outlook, regarding CO_2 capture from flue gas, the microencapsulation method seems the most promising at the short term and, in order to develop high selective solvent, experimental and theoretical approaches should be considered. On the other hand, for CO_2 capture from the air, more studies should be carried out to develop new tuned solvents and sorbents performing well also with humidity (because absorption and adsorption are most promising processes) able to reduce costs and energy consumptions as well as to scale up technologies at a lab scale. For CO_2 storage, mineral carbonation is a promising solution and new technologies with the same aim as well as new catalyst to accelerate the process are required in the future to reduce costs. Regarding CO_2 utilization in the future, studies must be conducted to improve efficiency and cost-effectiveness.

It is also recommended to undertake detailed lifecycle analyses of CO_2 capture, storage and conversion technologies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgments

The authors of the work would like to thanks the university of Cagliari for funding the work and the Imperial College London that allowed to carry out the work during the visiting research period.

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In this paper, the challenges of carbon dioxide capture and conversion are analyzed and pros and cons of the methods to remove these obstacles are suggested. The main challenges in carbon dioxide capture and conversion are reported: (1) energy consumption of current and alternative technologies, (2) costs, (3) insufficient activity, sustainability and economics of existing catalysts or microorganisms for carbon dioxide conversion, (4) environmental impact. It is the only paper present in the literature giving an exhaustive information on challenges of carbon dioxide capture and utilization.

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