Assessment of carbon capture techniques and their carbon sequestration potential, technical characteristics, and cost.

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Abstract

The scientific community has declared a need for urgent action on climate change to limit global warming to 1.5℃. To achieve this goal, carbon capture has been identified as a potential critical method. Currently, carbon capture facilities sequester around 45 megatonnes of CO_2 a year. The International Energy Agency estimates that around 1.2 gigatonnes of CO_2 must be removed by the year 2030 to stabilize the rate of global warming. This review compares the technical aspects, costs, and carbon sequestration potential of three carbon capture methods: direct air capture, biochar, and enhanced rock weathering. While direct air capture is the most developed and most reliable in sequestration ability of the three, it is more expensive than enhanced rock weathering and biochar, which are cheaper but more variable in sequestration.For these reasons, DAC is the frontrunner of carbon capture and holds the most potential in helping reach the 1.2Gt Target.

Introduction

The Intergovernmental Panel on Climate Change (IPCC) estimates that to keep the climate stable, global temperature rises must be limited to 1.5℃ annually (IPCC, 2018). The IPCC report predicts that if global warming exceeds this threshold, consequences could be irreversible: ecosystems could be lost, temperature extremes could increase, and sea levels could rise higher than if limited to 1.5℃ annually (IPCC, 2018).

While fluctuations in climate are considered natural phenomena, temperatures have risen dramatically due to increased emissions of greenhouse gasses by humans (NOAA, 2023). For millennia, atmospheric CO_2 concentrations have never exceeded 300 parts per million (ppm). However, in the last 200 years, CO_2 concentrations have increased by 50% to 422 ppm (NASA, 2023). This has raised the Earth's average temperature by 2°F since 1880, resulting in more frequent regional and seasonal temperature extremes (NOAA, 2023).

To achieve the goal of limiting global warming to 1.5℃, the IPCC projects that emissions must reach "net zero", or a state in which greenhouse gasses emitted to the atmosphere from human activities are balanced by removal of these gases from the atmosphere, by the year 2050 (IPCC, 2022). These gasses can be removed through carbon sequestration; the process of transporting CO_2 from the atmosphere into global pools such as oceans and geological strata (Lal, 2007).The IEA projects that to reach this goal, in addition to renewable energy, around 1.2 gigatons (Gt) of carbon dioxide (CO_2) must be captured each year (IEA, 2023). This is the same amount of CO_2 that 6.4 billion acres of forests remove annually (EPA, 2023). This amount must be removed through carbon capture and storage (CCS), where certain processes remove CO_2 from the atmosphere and then store it away either underground or in oceans (Tahmasebi et al., 2020).

This review assesses three different types of carbon capture methods at varying stages of development: Direct Air Capture (DAC), Biochar, and Enhanced Rock Weathering (ERW). DAC involves the extraction of CO_2 directly from the air, usually using one of two types of materials: liquid solvents or solid sorbents. Both materials react with and trap CO_2. These materials are heated up, releasing CO_2, which is stored away permanently in a storage facility (McQueen et al., 2020). Biochar, as defined by the International Biochar Initiative, is “a solid material obtained from the carbonization thermochemical conversion of biomass in an oxygen-limited environments” (IBI, 2022). Biochar can be composed of many different biomass sources, including food and plant waste. Because biochar stores CO_2, it does not require external storage and can be added to soil (cite). Similarly, ERW also does not require external storage, but instead has to process materials. This involves applying rocks rich in calcium and magnesium to soil to speed up the carbon removal process as the rocks naturally weather and react with CO_2 in the air (Beerling et al., 2020). This review evaluates DAC, biochar, and ERW’s potential to sequester carbon and consequently, their relevant economic and technical concerns.

1). Carbon Sequestration Potential

1.1 Direct air capture

Direct air capture involves the use of either solid or liquid sorbents to directly absorb CO_2 from the atmosphere (Fig. 1). After outside air is blown into contact with the sorbents, the filters are heated at low heat for an extended period of time to release the CO_2, which can then be stored away or reused for industries like the carbonated beverages industry.

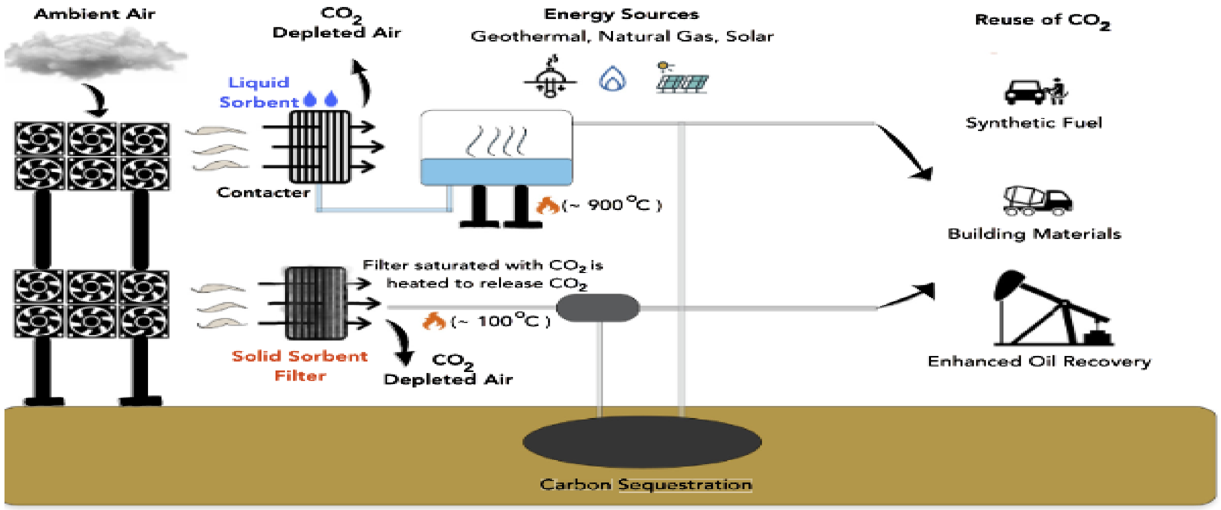

Figure 1. Direct Air Capture Process (Ozkan et al., 2022)

As of 2023, around 27 DAC plants are active, with six new plants under construction, capturing about 0.01 megatonnes (Mt) CO_2 per year (IEA, 2023). A recent systematic review found that the carbon sequestration potential for DAC is 0.5–5 Gt CO_2 per year, which is the equivalent of the CO_2 sequestered by 6 million to 6 billion acres of forests (Fuss et al., 2017; EPA, 2023). While the sequestration potential of DAC as a whole is often understood to be unlimited due to DAC’s stable sequestration rate, DAC is held back by high sorbent costs and technical considerations, mainly storage (Fuss et al., 2017).

Sabatino et al. (2021) found a difference between solid and liquid sorbents and the amount of CO_2 captured over time per unit of sorbent volume, or “productivity”. They found lower ranges of productivity for liquid-solvent processes than solid sorbent processes due to . Additionally, there was a distinction found between different types of compounds: physisorbents, which are based on crystalline compounds consisting of metal ions, and chemisorbents, which are based on amines (Leonzio et al., 2022). Leonzio et al. (2022) found physisorbents were not only more expensive and less energy efficient than the chemisorbents, but they also sequestered less CO_2 (Leonzio et al., 2022). DAC plants using physisorbents also had lower sequestration results than chemisorbent-using ones due to the higher amount of sorbent needed and higher energy costs (Leonzio et al., 2022).

Many studies do not consider storage or transportation of CO2 aspects, despite this being the main limitation of DAC. (Sabatino et al., 2021). While in the US, there is enough storage space to easily store trillions of tons of CO_2, these spaces are not developed enough (DOE, 2023). Additionally, a study found that CO_2 storage underground in depleted oil and gas fields is not readily available for commercial scale (Bui et al., 2018). Overall, DAC's high sequestration rate makes it very promising for reaching "net zero", but its efficacy depends on the type of sorbent used and the availability of storage.

1.2 Biochar

While DAC requires external storage of CO_2, biochar itself stores carbon. Biomass undergoes carbonization, usually through pyrolysis, or the process of transforming a material by heating it to a very high temperature in the absence of oxygen (Tam & Bhatnagar, 2016). Thus, biochar can be made from many different sources of biomass, making the process very practical.

Although there are several sources of solid biomass for biochar, different feedstocks, or the raw materials used, can affect the sequestration potential (Yargicoglu et al., 2015; Ahmed et al., 2007; Masek et al., 2018). Specifically, feedstock consisting of woody biomass was found to produce biochar suited for sequestration purposes, having higher amounts of fixed carbon (Yargicoglu et al., 2015). Biochar made from the date palm leaf could sequester up to 25% of the CO_2 inside of a closed container in addition to the carbon stored inside the biochar itself (Salem et al., 2021).

A challenge of relying on biochar for carbon sequestration is the inconsistency in sequestration that comes from using different materials. Sadasivam & Reddy (2015) found that the physical and chemical properties of biochar "significantly impacted" the sequestration potential of greenhouse gases, with certain materials unable to adsorb as much. Even among specific types of biochar, including those derived from wood, sequestration potentials varied wildly (Yargicoglu et al., 2015). Biochar's quality can also be affected by the uniformity of the feedstock, the type of pyrolysis process used and any carbon losses from the biomass before it enters pyrolysis (Masek et al., 2018). To address these concerns, the UK Biochar Research Centre (UKBRC) developed a set of standard biochar materials, known as the Edinburgh Standard Biochar set, which were made freely available to research groups around the world (Masek et al., 2018). Masek et al. (2018) found that when using these materials, different types of pyrolysis units were able to produce similar biochar with consistent quality parameters, albeit not at an industrial scale. Biochar's inconsistency in its carbon sequestration rate remains its largest obstacle to its adoption on a large scale.

1.3 Enhanced rock weathering

ERW also suffers from a lack of consistency arising from the materials used. However, unlike biochar, the rocks do not store carbon, rather they accelerate the natural weathering process. After the rocks are mined, they are ground into fine particles to increase their surface area, which speeds up the weathering reaction. These particles are spread on land, usually cropland. Next, the CO_2 in the atmosphere combines with rainwater and forms carbolic acid (Fig. 2). This acid reacts with the rocks scattered on the field, forming solid carbonates, which are then washed into the sea for storage in the ocean.

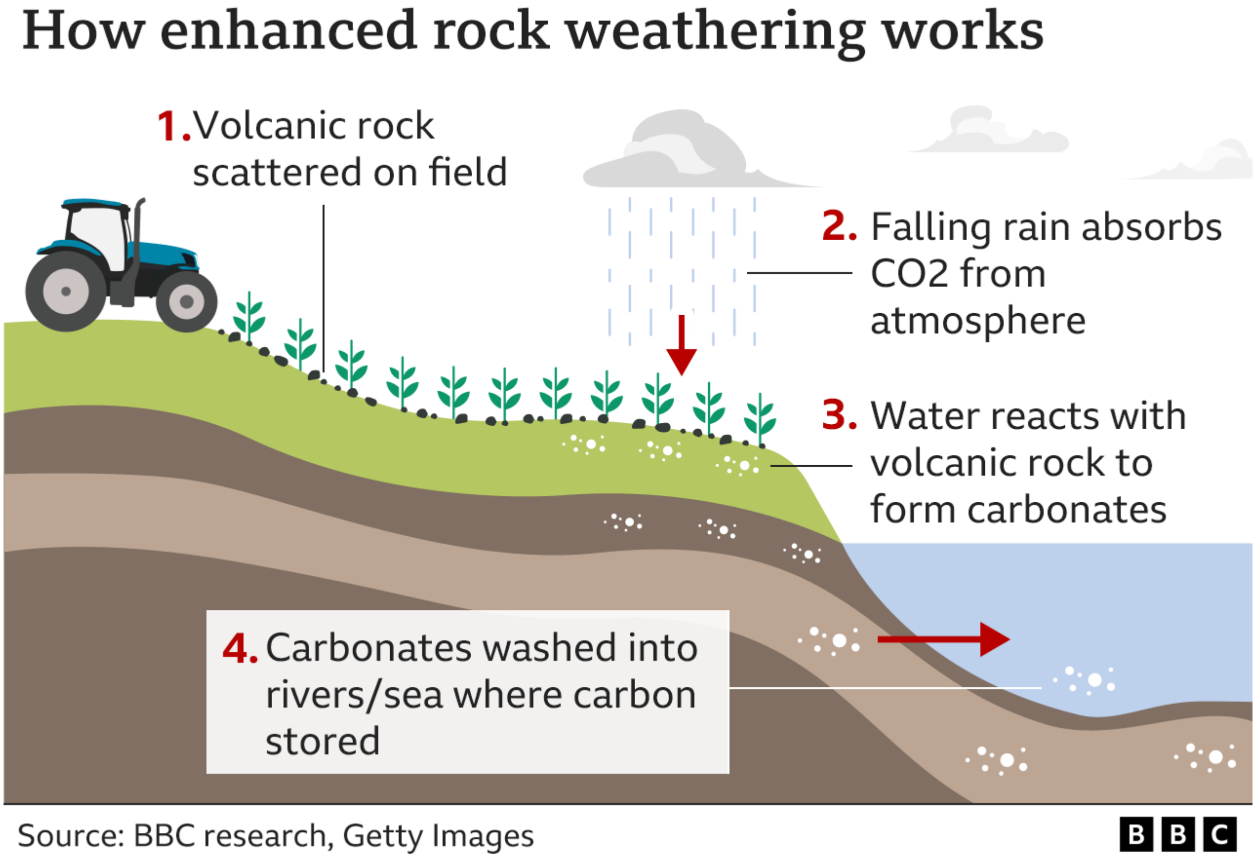

Figure 2. How enhanced rock weathering works (BBC, 2023).

The most common rock used for ERW is basalt, however other studies have used dunite and olivine (Strefler et al., 2018; Garcia et al., 2020; Rigopoulos et al., 2018). Strefler et al. (2018) found global sequestration potentials of 4.9 Gt of CO_2 annually for basalt and 95 Gt of CO_2 annually for olivine. While these rocks are relatively good at sequestering CO_2, the main issue for its carbon sequestration potential is that the mining, processing, and transportation all emit CO_2, effectively lowering the net sequestration of ERW. Ioannis et al. (2017) found that the processing of the rock into fine particles could reduce the overall sequestration of ERW by 30%, and the mining required could reduce it by an additional 0.1-1%.

2). Costs / Technical concerns

These three technologies have a wide range of costs and technical concerns. DAC is the most expensive and energy-intensive technology, but is also the most developed in terms of sequestration potential. Biochar is much cheaper, but its effect on soil has not been thoroughly researched. ERW is more expensive, but has a lower range of technical concerns.

2.1 Direct Air Capture:

DAC, the most expensive of the three, has the fewest technical challenges. Unlike ERW or biochar, DAC's sole purpose is carbon capture, so its environmental impacts are usually neglected or assumed to be minimal (Ozkan et al., 2022; McQueen et al. 2021). The main barrier to DAC's use is its cost. A study by Bui et al. (2018) estimated DAC's costs to be in the $600-1000 range per ton of CO_2. The bulk of this cost comes from purchasing sorbents, with it being estimated that sorbents consist of around 80% of the total annual capital cost of a DAC plant (McQueen et al., 2020). While scientists generally agree more research needs to be done on the sorbents themselves, they have also found a variety of other ways to decrease DAC's cost (Ozkan et al., 2022; McQueen et al.*,*2021). McQueen et al. (2021) suggests that DAC's cost could naturally decrease through a learning curve or learning by doing, in which research and development advance the technology and lower costs. Additional reductions could come from cost subsidies, which the US currently has in the form of tax breaks for any DAC facility that removes at least 100 kilotons of CO_2 per year (McQueen et al., 2020).

The other major barrier to DAC's adoption is its energy requirements and the associated cost. DAC requires a specific ratio, around 80% thermal energy and 20% electricity (McQueen et al., 2020, McQueen et al*.,* 2021). Ozkan et al. (2022) estimated the energy required for DAC is 6.57-9.9 gigajoules (GJ) to capture a ton of CO_2 for liquid processes and 3.5-6.6 GJ for solids. This is the same amount of energy produced by around 170-257 liters of gasoline (FortisBC, 2023). This higher energy cost means that renewables would have to be used to power DAC, otherwise the fossil fuels used could release more than half the CO_2 captured by DAC (Ozkan et al., 2022).

To decrease these energy requirements, scientists have tried a variety of approaches. Ozkan et al. (2022) showed that solid sorbents require less energy per ton of CO_2 sequestered. Per ton, solid sorbents required between 32% and 44% less energy for heating. Additionally, using heating, ventilation, and air conditioning (HVAC) systems to recirculate heat could substantially reduce energy consumption. Baus and Nehr (2022) found that it reduced the energy demand of a building by 37%. This drastic reduction could give DAC a unique use in improving indoor air quality. DAC remains the main sequestration option even with these concerns.

2.2 Biochar

Biochar, while cheaper than DAC, has varying costs and under-explored impacts on the land it is applied to. While using waste biomass can be very cheap, using virgin, or pure, biomass can raise the costs to over $120 per ton of CO_2 sequestered (Shackley et al., 2014). For waste biomass, costs still vary, but by less. Shackley et al. (2014) found costs of around $27 per ton of green waste, $61 per ton of wood waste, $43 per ton of food waste, and $55 per ton of sewage. Additional costs can come from transportation and application of biochar. Despite this, biochar remains significantly cheaper than DAC.

Biochar's main issue comes from its effects on the land. There have been few long-term studies on biochar and many of its effects are undocumented (Shackley et al., 2014, Gross et al., 2021, Ahmed et al., 2007). While biochar's impacts are likely to be positive for the environment, a great deal of uncertainty surrounds these impacts (Xie et al., 2015; Palansooriya et al., 2019; Dickinson et al., 2014). Biochar's impact on soil productivity, water quality, or even the general environment have yet to be measured (Ahmed et al., 2007, Shackley et al., 2014). Because of this, it becomes very difficult to extrapolate what kind of large scale effects could have on the environment. Due to these blind spots, biochar's safety as a carbon capture method is questionable.

While biochar is very cheap, its properties may not be worth the cost. The benefits of biochar for agriculture are modest at best, and the lack of understanding around biochar makes it risky to use. Dickinson et al. (2014) found that, combined with biochar's cost, its limited benefits make biochar a relatively poor option for cereal farmers. Biochar's merits outside of carbon capture are limited, lowering its potential as a general product.

2.3 ERW

ERW acts as a middle ground between DAC and biochar. While not nearly as cheap as biochar, ERW's effects on the environment are well documented, with fewer variables to account for. Unlike biochar, ERW's difference in its costs for different materials stems purely from sequestration potential, with it costing around \$60 to sequester a ton of CO_2 with dunite and \$200 with basalt (Strefler et al., 2018). This cost can vary depending on the distance transported, processing time, and electricity prices for mining and crushing. Strefler et al. (2018) maintains that while these costs are high, ERW could become more competitive if its benefits to the soil or nutrient supply are taken into account.

Other than sequestration, ERW has a variety of benefits to the environment. Basalt particles can increase soil pH, replenish nutrients, and even potentially protect against droughts (Garcia et al., 2019). These benefits make it incredibly useful for farmers, and even a possible substitute for industrial fertilizers. Additionally, ERW has the potential to fight another effect of climate change: ocean acidification (Rigopoulos et al., 2018, Strefler et al., 2018). Seawater normally has an average pH of 8.2, but since the Industrial Revolution, the average pH has decreased to 8.1 pH, which is an acidity increase 100 times greater than any natural rise seen over millions of years (WHOI, 2023). Higher CO_2 levels are to blame for this increase, with more carbolic acid being formed as the ocean absorbs more CO_2. These additional benefits make ERW very appealing as a carbon capture method.

ERW's main challenges come not from its price, but the scale of mining and processing needed for the process to be scaled up. Strefler et al. (2018) found that it takes around 3 Gt of basalt to sequester one gigaton of CO_2, which, while technically feasible due to being below global coal production, would still require a large amount of mining. Additionally, the processing required for ERW to function on a large scale could also cause severe wearing of milling equipment, which would decrease efficiency (Haug et al., 2010). Overall, ERW remains a strong sequestration option, but requires optimization of mining, processing, and transportation as well as further research on its effects on the land.

3. Conclusion

To combat climate change, carbon capture technologies will be instrumental in keeping global temperature raises under two degrees Celsius. Three of the main carbon capture technologies, DAC, biochar, ERW, have been considered in this review. DAC benefits from consistency in its sequestration potential but is held back by high costs, lack of consensus on storage, and energy requirements. Biochar, on the other hand, has lower costs but higher uncertainty in its sequestration efficiency and environmental impacts. ERW is expensive but has lower costs than DAC, is more reliable as a carbon capture method than biochar, but is held back by the scale of mining and processing needed if ERW becomes widely used. Prioritizing direct air capture could be most successful in reaching the 1.2Gt target, given that its issues are not fundamentally with the technology itself, but rather the cost and energy intensity of the process. Additionally, DAC is by far the most developed technology, with it being the only technology that is currently supported by subsidies in the US. For these reasons, DAC is the frontrunner of carbon capture and holds the most potential in helping reach the 1.2Gt Target.

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